Overhead Radiation and Comfort

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SUMMARY

Overhead radiant heating produces an environment which is asymmetric, and it is possible for this asymmetry to cause discomfort. This paper summarises five experiments that have been carried out in the ECRC thermal environment chamber on the reactions of people to overhead radiation. Concurrent with the experimental work has been the development of a theory of the thermal radiation field, which enables a radiation environment to be described in terms of simple units. The asymmetry is measured by the vector radiant temperature (v.r.t.). The v.r.t. is a temperature difference measured in degrees Kelvin, and may be visualised as the average surface temperature of one half of a room minus that of the other.

From the evidence of our own and other experiments it is shown that a vector radiant temperature of greater than 10K in an occupied space produces noticeably non-uniform conditions, and is likely to lead to complaints. It is recommended that a maximum v.r.t. of 10K be taken as the criterion for acceptability for non-uniform environments.

The v.r.t. is related to both the size and the temperature of the heated ceiling panel, and hence to the heat output of the panel. In practice this sets an upper limit to the heat emission that may be obtained from the panel without increasing the v.r.t. beyond 10K.

This paper presents graphs which give the maximum recommended ceiling temperature as a function of the dimensions of the heated panel. For rooms of normal height, the maximum installed load P_{max}(W) is related to the heated panel area A (m^2) by

$$P_{max} = 700 + 95A$$

This simple relation is to be used at the design stage to check the acceptability of a system.

1 INTRODUCTION

Several radiant heating systems employ overhead, downward facing, heat emitters. The range of systems is large, from low temperature ceiling heating for domestic applications, to high temperature gas fired units designed for industrial use. Each system has its own particular advantages, which decide its field of application. This paper is concerned with the environmental conditions produced by radiant systems, how they are perceived by the occupants of the heated space, and with avoiding any possible discomfort.

The first requirement of a heating system is that it should make people warm enough. The physical parameters of the thermal environment which affect warmth are air temperature, mean radiant temperature and air speed. Humidity is only of importance in situations of warm discomfort, and will not be considered here. Radiant heating systems produce an environment in which the mean radiant temperature (T_r) is higher than the air temperature (T_a); the reverse holds for warm air systems. The conduction loss through the walls is best predicted by the environmental temperature $T_{ei} = \frac{2}{3} T_r + \frac{1}{3} T_a$. It is not however the best predictor of warmth. We have adopted the term subjective temperature for the temperature index which best predicts the warmth of an environment, to differentiate it from environmental temperature. At low air speeds the subjective temperature is given by $T_{sub} = 0.56\, T_a + 0.44\, T_r$[9]. An earlier paper[6] in this journal looked at the question of radiant versus warm air heating, and presented experimental results which showed that people do not distinguish between radiant or warm air environments. In particular, we found no evidence at all to support the common idea that radiant environments, with $T_a < T_r$, are perceived as "fresher" or more invigorating than warm air environments. This finding was based on experiments in which the environments were very uniform i.e. there were no temperature gradients in the air, and all room surfaces were at the same temperature, so there was no directional radiation. This paper deals with asymmetric radiant environments i.e. the situation where the radiant heat comes predominantly from one side. It is perfectly possible to produce an environment which has the right level of warmth, but which is uncomfortable because of the directionality of the radiation. It is important to keep the distinction clear between warm discomfort and discomfort caused by asymmetry. The warmth of an environment depends on air temperature and mean radiant temperature; discussion of the radiant asymmetry requires the use of another unit, the vector radiant temperature (v.r.t.).

The v.r.t. is a simple, and physically meaningful, way of quantifying the radiant asymmetry at a point in space. Its units are those of temperature difference, and it may be thought of as the average surface temperature of one half of the room minus that of the other. It is a vector quantity, having direction as well as magnitude. Appendix 1 gives the formal definition of vector radiant temperature, and notes on how to calculate or measure it.

Several experiments have been carried out at ECRC Capenhurst on the influence of asymmetric radiation on comfort. This paper summarises them briefly, and then by comparing their results with those of other workers, it is shown that a simple comfort criterion may be developed, the use of which should help considerably to avoid any possible problems with overhead heating.

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2 THE EXPERIMENTS AT CAPENHURST

2.1 General Conduct

All the experiments were carried out in the ECRC Thermal Environment Chamber. This is a room of dimensions 3.7 × 3.7 × 2.4m. Conditioned air of the required temperature and humidity enters the chamber through a permeable floor, and is extracted through grilles set at the top of the walls. By this means the large volume flow of air necessary for good temperature control can be achieved at low air speeds without any draughts. The wall and ceiling temperatures are independently controllable.

The radiation vector is measured by a net radiometer (Solar Radiation Instruments Model SRI 4); this instrument was only obtained recently, and in the earlier experiments the radiation vector was calculated from the known surface temperatures and dimensions of the chamber. A computer program was necessary to handle the cumbersome form factors.

In all but one experiment, four subjects came at a time. The seating positions are summarised in Fig 1.

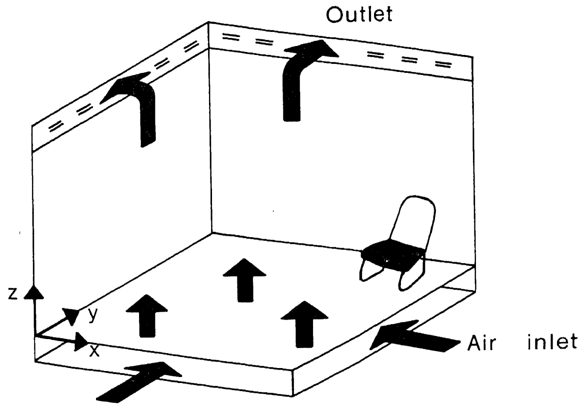


Fig 1 Air enters the chamber through a permeable carpet, and is extracted through grilles at ceiling height. The four subjects sit symmetrically in the corners of the room, facing inwards to the centre. The seat position was about 1m from each of the walls, except in experiment E, where the single subject sat in the centre of the room.

Since the aim of our investigations was to produce a design criterion that would apply to the population, it was necessary to work with large groups of subjects. The use of large groups is also necessary for statistical purposes, since the large variation in response, both between different people, and within the same person's response on different occasions, makes it necessary to apply statistical tests to differentiate between real and chance effects.

The use of statistical tests means that a subject's reactions to the environment have to be quantified in some way. The standard technique used at ECRC is to ask the subject to evaluate his feelings on a seven point scale. As an example, the 'pleasantness' scale runs from 1 Pleasant to 7 Unpleasant

The subject assesses the degree of pleasantness by choosing a number between 1 and 7 that best indicates his feelings. In the early experiments over 30 different scales were used, to find which were the most sensitive and reliable. In the later experiments the number was reduced to eight

For most of the experiments described in this report the subjects sat in the chamber for 45 min, reading, talking, writing or some other sedentary activity. Before entering the chamber they removed jackets or pullovers and so a roughly constant level of clothing insulation was maintained. We have found that 45 minutes is a sufficiently long period of exposure and people have settled down by this time. Votes do in fact continue to change slowly with longer exposure, but this is not important since our aim is to make a comparison between different conditions at the same exposure time.

After 45 minutes the subjects were instructed in the use of the rating scales. The questions were presented by slides from a projector.

Experimental designs may be of two types. In the repeated measure design each subject returns to experience all the conditions. In the final analysis the different votes cast by a subject over the experimental conditions are compared with themselves i.e. 'within subjects'. In this way any differences between subjects do not add to the scatter. This type of analysis is more sensitive in detecting differences between conditions than the non-repeated measures design, in which each subject only attends once. The non-repeated measures design has the advantage that there is no possibility of unwanted effects, where the way a subject behaves in one test may be affected by what happened in the previous test.

At the end of the experiment the votes are totalled to obtain the mean score for each condition. It is then necessary to test whether any difference between the means is caused by the experimental conditions, or is merely a chance effect. The testing process used is termed analysis of variance, and the results are expressed in terms of significance levels. A significance level of 5 per cent means that the observed result would arise by chance on one out of twenty trials, and we therefore suppose that there is a real effect.

2.2 The five experiments summarised

Five separate experiments on overhead heating were carried out at ECRC. The first, A, was a straightforward exposure of the subjects to overhead heating, with air and mean radiant temperature held constant at a comfortable level. The second was a shorter version of the first, but carried out at a higher ambient temperature, corresponding to a mean Bedford vote of 'comfortably warm'; this was to check if people were more sensitive to overhead radiation at higher temperatures. No increase of mean discomfort vote was found at a v.r.t. of 20 K, and accordingly it was suggested that a v.r.t. of 20 K be taken as the acceptable limit for asymmetric radiation.

The first two experiments held air temperature and mean radiant temperature constant; at high ceiling temperatures the wall temperatures were reduced by the appropriate amount to compensate. It was found, however, that subjects felt cooler in the hot ceiling condition than in the uniform condition. A seated body is not symmetrical, and presents a greater area for horizontal radiation than for vertical. However, when allowances were made for this, it was still found that the subjects were unexpectedly cool when sitting under a hot ceiling with their backs to a cold wall.

Experiment C made a direct study of this cold wall effect, including the reverse situation of warm walls and cold ceiling. The warm wall condition was not perceived as different from uniform, but the hot ceiling/cold wall situation was definitely felt as cold.

Experiment D looked at the effect of panel size, by asking for ratings of situations of the same m.r.t. and v.r.t., but produced by panels of different size and temperature. This found little difference between the conditions.

The final experiment had the aim of bridging the gap between earlier ECRC work and continental experiments which had found lower acceptable levels of radiation. Air and wall temperatures were held equal, and reduced together to compensate for the hot ceiling. As well as using the normal seven point scales for general feelings, subjects answered questions which referred specifically to the hot ceiling. It was found that subjects attributed discomfort to the hot ceiling even when the average comfort vote showed an improvement. This experiment led us to reduce the recommended limit.

Each experiment is summarised briefly in Appendix 2. Full experimental details are given in the relevant ECRC publication.

2.3 Results

2.3.1 *General discomfort*

This refers to questions which asked the subjects to rate their general feelings e.g. comfort, pleasantness, discomfort, etc. None of the five experiments found any worsening in comfort vote for vector radiant temperatures up to 20 K. Only a v.r.t. of 37 K produced by an overhead panel running at 700°C, and enhanced by placing the subject near a 15°C wall, gave a significant increase of discomfort. An overhead medium panel (Experiment C) and a 45°C ceiling with the subject centrally placed (Experiment E) in fact gave a significantly better mean comfort vote when compared with uniform conditions.

2.3.2 *Cold Wall Effect*

In the first three experiments subject under a 45°C ceiling, sitting with their backs to cool walls, reported that they were cooler than they were in uniform conditions with the same m.r.t. The decrease in warmth was 0.8 of a scale interval on the Bedford scale, of which 0.3 could be explained by the asymmetric shape of a seated person. It seems that people do not integrate the thermal exchange over their body surface, but consider themselves cool when their back is cool, inspite of compensating warm radiation from other directions. The effect was not observed in either D or E. In E the subject sat in the centre of the chamber, and the wall temperature was not as low as in A, B and C.

2.3.3 *Discomfort attributed to overhead radiation*

In the first four experiments the subjects were not told that the experiment was concerned with overhead heating. While it was clear from their responses that they could detect the radiation, the questions on comfort referred only to general feelings. The final experiment was different in that, after some general questions, the subject was told that the ceiling was hot, and asked how noticeable it was, and how much discomfort was caused by it. This produced the apparently paradoxical result of general comfort and pleasantness increasing as the ceiling temperature rose, while the amount of discomfort attributed to the ceiling also rose. It seems that then the overhead radiation becomes noticeable, people are ready to blame it for discomfort, even though their general rating of discomfort is not worse.

3 DISCUSSION

3.1 Other workers

Although several experiments on discomfort from asymmetric radiation have been reported in the literature, it is not straightforward to compare their results. It has been necessary to go back through the literature and calculate the radiation field experienced by the subjects. One of the first investigations, and one which had a great influence in setting comfort recommendations in Europe, was that by Chrenko[4]. In that experiment no attempt was made to control for the increase in m.r.t. produced by the warm ceiling panel. Any discomfort experienced by the subject was therefore caused by some unkown combination of asymmetry and overheating. It is worth remembering in this context that Fanger's PPD (predicted percentage dissatisfied) curve[4] shows that a small change in temperature may increase the PPD of a group by a surprisingly large amount. The physical measure used by Chrenko was the elevation of m.r.t. at head level; the concept is rather unclear, and difficult to apply to other situations. The original paper also gave recommended maximum ceiling temperature as a function of ceiling height and dimensions.

Those experiments which have controlled the m.r.t. at a constant value show a high tolerance to asymmetric radiation. McNall and Biddison[12] exposed people to a hot ceiling which had a temperature as high as 54°C. Mean radiant temperature was held constant at 25.6°C by reducing the wall temperatures an appropriate amount. The maximum v.r.t. is estimated to have been 24K. No significant increase of discomfort vote was found compared with a uniform control condition. In contrast, McNall and Biddison found that a horizontal asymmetry produced by a hot wall gave rise to a higher warmth vote and an increase in discomfort vote, when compared with the uniform condition. Calculated v.r.t. was 24K.

Olesen et al.[15] looked at the effects of lateral asymmetry. The nude subject sat in the centre of the environmental chamber, which was maintained at the temperature he found most comfortable. The temperature of a side wall was then raised by 5 K and that of the opposite wall reduced by 5K; the m.r.t. therefore remained constant. The temperature difference was increased by a further ±5K every half hour until a maximum of ±20K was reached. At 10 min intervals the subject was asked whether he could detect the difference between the end walls, and whther it caused him discomfort.

The authors took 5 per cent uncomfortable as their criterion, and recommended a v.r.t. limit of 10K for nude subjects. On the assumption that local cooling was the main cause of discomfort Olesen estimated the v.r.t. which would produce complaints in clothed subjects. For a clothing insulation of 0.7 clo units, corresponding to typical indoor light clothing, the recommended value is 20K.

Banhidi[1] produced a recommended upper limit to ceiling temperature expressed in terms of form factors; when converted to vector radiant temperature, his limit is equivalent to a v.r.t. of between 8.5 and 13K depending on the angle subtended by the ceiling. Schroder & Steck[16] were interested in the potential problem of thermal discomfort caused by radiation from lights. They exposed subjects to the radiation from a bank of fluorescent lamps. The subjects were asked directly whether they found the heat radiation from the lights disturbing. Taking a 5 per cent response of "disturbing" as a criterion, the authors recommended a v.r.t. of 9K as a limit.

The results of the experiments are summarised in Table I along with those of our own at ECRC. There is general agreement. Those experiments which asked the subjects to assess the overall comfort showed no effect of directional radiation. V.r.t.'s of up to about 20K were employed by McNall and Biddison and in experiments A, B and D at ECRC without producing any significant worsening of the comfort vote. Those experiments which asked the subjects specifically about the overhead heating produced lower limits.

The difference between the two sets of results lies in the way people use comfort scales. The seven point overall comfort scale is fairly insensitive to changes in environmental conditions. The standard deviation of the comfort votes of a group of people is high at about 2 scale intervals. This implies that in any situation, even one which must be regarded as generally 'comfortable', there will be a substantial proportion of people who consider themselves uncomfortable. When offered the chance of attributing their discomfort to an identifiable cause such as overhead heating, it seems that they will do. Thus the final experiment E in the Capenhurst series shows the apparently paradoxical results of the mean overall comfort and pleasantness votes *improving* as the temperature increases, while the number of people suffering discomfort from the ceiling heating *increases*. It does not seem profitable to pursue the argument whether the subjects were really more uncomfortable under a hot ceiling. A considerable fraction attributed discomfort to the hot ceiling and in a real life situation this would be likely to produce complaints. There is the danger that ceiling heating, being identifiable, might be blamed for discomforts which are really unidentified.

3.2 Comfort limits for asymmetry

Our findings, together with those of other workers as summarised in Table I, show that for subjects in thermal neutrality a vector radiant temperature of 20K does not increase the average discomfort of a group. However, this level of radiation is noticeable, and the results of Experiment E, together with those of Schroder & Steck, indicate that people are ready to attribute feelings of discomfort to the perceived radiation. It is therefore recommended that a vector radiant temperature of 10K be taken as a suitable upper limit.

There is no firm evidence that the temperature of the radiant source affects comfort, though of course the use of small high temperature sources is likely to lead to positions where the recommended v.r.t. is exceeded. There was a suggestion from Experiment D that warm radiation on the face was disliked; this has not been tested. The first three experiments all found that subjects sitting with their backs to a cold wall produced unexpectedly low warmth votes; this is similar to Olesen's finding that subjects were more tolerant of a cold surface in front of them than behind them.

3.3 Application to overhead panels

The vector radiant temperature, T_v, may be predicted from a knowledge of the room dimensions and surface temperatures. The general calculation is complicated, and summarised in Appendix 1. The position is greatly simplified if we can assume that all unheated surfaces are at the same temperature T_u. If the ceiling panel temperature is T_c, and we may apply the linear approximation,

$$T_v = F_{pc}(T_c - T_u) \qquad (1)$$

$$\text{and} \quad T_r = F_{sc}T_c + (1 - F_{sc})T_u \qquad (2)$$

where F_{pc} is the form factor from a plane element at the test point to the ceiling and F_{sc} is the form factor

Table I Summary of experiments on asymmetric radiation

Reference	Maximum v.r.t. used (K)	Vertical or horizontal radiation?	Constant warmth?	Direct Question?	Recommended limit of v.r.t. (K)
2	20	V	No	Yes	About 6
12	24	V	Yes	No	No discomfort found
12	24	H	Yes	No	Discomfort found
15	16	H	Yes	Yes	10 Nude 20 Clothed (extrapolation)
1	-	V	No details given		8 to 13.5
16	10.5	V	No	Yes	9
ECRC (A)	20	V	Yes	No	20
ECRC (E)	16	V	Yes	Yes .	10

from a small sphere to the ceiling. Eliminating T_u gives:

$$T_c—T_r = (1—F_{sc})T_v/F_{pc} \qquad (3)$$

F_{pc} and F_{sc} are functions of the size and height of the heated panel. Equation (3) has been solved for a point under the centre of a square panel, and the results are shown in Fig 2. This shows the value of $(T_c—T_p)$ as a function of h/a, where h is the distance from test point to ceiling, and a is the side of the square panel.

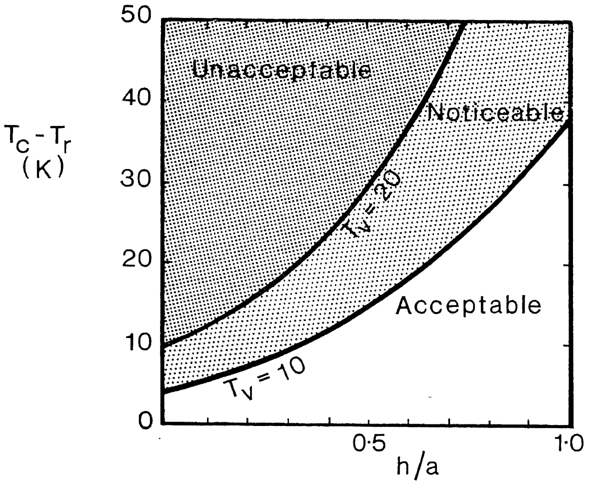


Fig 2 Permissible elevation of the temperature, T_c, of an overhead square panel above the mean radiant temperature, T_r, of a room as a function of panel height h and side a.

For example, a domestic ceiling heating installation might have a panel size of 3 × 3m; a suitable position for the test point is 1.5m below the ceiling (roughly seated head height). This gives $h/a = 0.5$, and $T_c—T_r = 15$K for a v.r.t. of 10K. The m.r.t. for comfortable conditions will be about 23°C, so that the maximum permitted ceiling temperature is about 38°C. This is higher than normal practice, so we should not expect ceiling heating to produce complaints. The poorer the insulation of the building, the higher the ceiling temperature required to emit the necessary power into the room. Thus poor insulation will increase the asymmetry and the risk of complaints. By making reasonable assumptions about heat transfer from a ceiling panel, equation (3) may be rewritten in terms of the emission fron the panel. The air temperature in a room heated by the ceiling will be close to the average unheated surface temperature, and so the total downward emission H(W/m^2) from the heated ceiling panel is

$$H = (h_c + h_r)(T_c — T_u) \qquad (4)$$

For this treatment it is sufficient to use the linear approximation to radiant heat transfer, with $h_r = 6.1$ W/m^2K. The convective transfer coefficient h_c is about 1 W/m^2K for downward transfer, where there is no flow round the edge of the panel. Equation (1) gives the v.r.t. in terms of $(T_c — T_u)$, and so equation (4) may be rewritten

$$H = 7.1\, T_v/F_{pc} \qquad (5)$$

This equation has been solved to give the heat emission which produces a v.r.t. of 10K at a distance 1.5m below a square panel, Fig 3. The figure shows both total emission and emission per unit area, to emphasise that the permissible emission per unit area decreases as the panel size increases. Fig 3 has been calculated for square panels. The error in H is less than 10% for aspect ratios of the panel less than 2. For greater aspect ratios it will be necessary to calculate the form factors directly from Appendix 1.

Fig 3 shows the downward emission from a panel which will produce a v.r.t. of 10K, and hence this is the

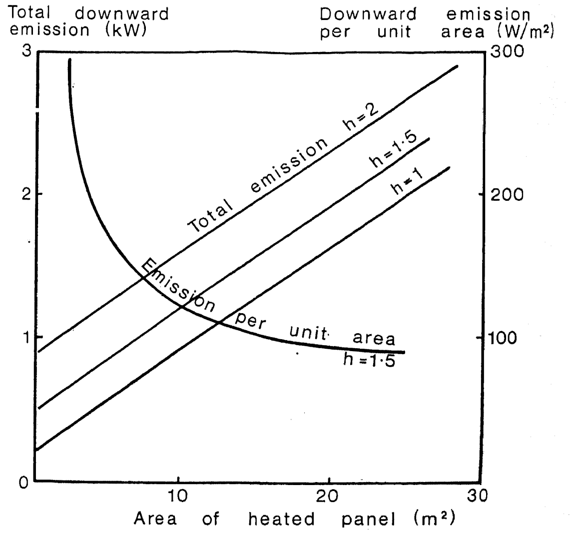


Fig 3 The downward heat emission of a square overhead panel which will give a v.r.t. of 10K at a distance h below the centre of the panel.
Add 30 per cent to the downward emission to obtain total dissipation of heater element for normal installations. The figure may be used for non-square panels up to an aspect ratio of 2:1.

maximum recommended emission. To be of practical use, the figure must be related to the installed load. Conventional installation practice employs at least 75mm of insulation over an element on the top storey, and 50mm over an element of an intermediate floor. In both cases, this allows about 15 per cent of the total power to escape upwards; this heat does not of course contribute to the radiant field in the heated room. It is also common practice to oversize the element by about 15 per cent to ensure an acceptably fast rate of warm up. This extra load will appear as an increase in the vector radiant temperature. This increase in asymmetry will only occur during the warm up period, and it has been assumed that it will be acceptable.

The curve of downward emission versus area in Fig 3 may be simply represented by a straight line, and we may write a simple relationship between the maximum downward emission H_{max} (W) of a panel and its area A (m^2)

$$H_{max} = 500 + 70A\ (h = 1.5\text{m})$$

Allowing for the factors mentioned above, this may be converted to a relation for the maximum installed load P_{max} (W/m^2);

$$P_{max} = 700 + 95A\ (h = 1.5\text{ m}) \qquad (5)$$

This equation holds for a ceiling height of 1.5m above

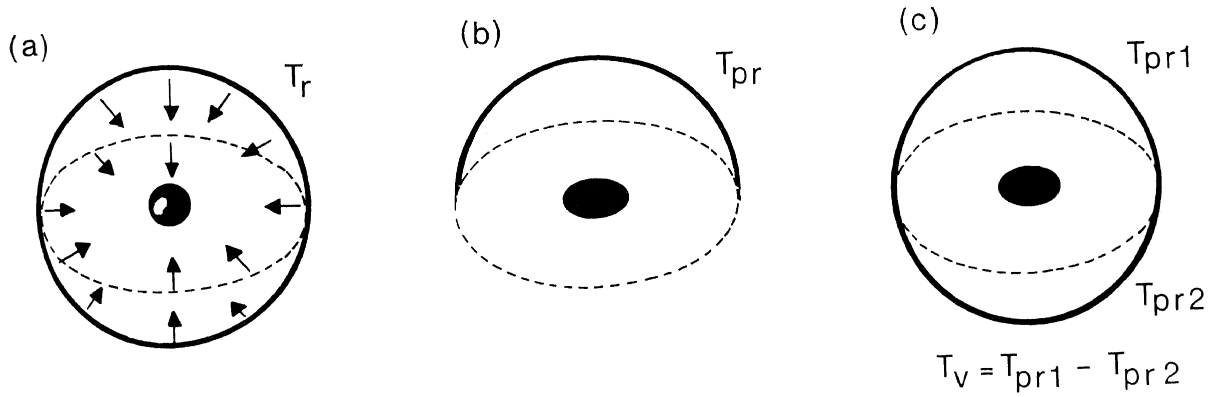


Fig 4 The parameters of the radiation field$_r$

(a) *Mean radiant temperature, T_r, is the temperature of a uniform sphere which would produce the same radiation on a small sphere as exists in the real environment.*

(b) *Plane radiant temperature, T_{pr}, is the temperature of a uniform hemisphere which would produce the same irradiance on a small plane element as exists in the real environment.*

(c) *Vector radiant temperature, T_v, is the difference between the plane radiant temperatures on opposite sides of a plane element, The element is oriented in space to give a maximum value T_v.*

the occupied region, and its appropriate for normal installations where people are predominantly seated. For other heights we have

$$P_{max} = 1200 + 95A\ (h = 2m)$$

$$P_{max} = 300 + 95A\ (h = 1m)$$

These equations provide a useful check on the possibility of producing uncomfortable conditions with a ceiling heating system. The design procedure for sizing ceiling heating is set out in Electricity Council Direct Electric Heating Design Manual.[3] The heat loss from the room to be heated is estimated for a design day, and increased by 15 per cent or more to produce more rapid response. The heating elements are thus laid out to produce the required loading. This load should then be checked against equation (5) above to ensure that the maximum recommended asymmetry of a v.r.t. of 10K is not exceeded. If it is, the conditions in the room will be noticeably non-uniform, and may lead to complaints. A well insulated house is most unlikely to exceed the limit but a conventional building, particularly if the heated room has large windows or two exposed walls, may well require more than recommended maximum loading. Steps should be taken to reduce the loading; in practice this will mean the provision of higher levels of insulation.

It should be remarked in this context that gypsum plasterboard changes structure and loses strength at temperatures above 42°C.[14] The ceiling surface temperatures may be estimated from equation (4). Assuming, as before, that 15 per cent of the total heat dissipation is transmitted upwards, the ceiling temperature is given by

$$T_c - T_u = 0.12\,P/A$$

where $(T_c - T_u)$ is the difference between the ceiling temperature and the rest of the room, and P/A is the loading of the heated panel in W/m^2. A check list of materials that have been found satisfactory in practice is given in reference (3).

The recommendations given above are designed so that discomfort from asymmetric radiation may be avoided when using ceiling heating. They cannot guarantee comfort; it is still necessary to follow normal good practice to avoid discomfort from other causes. Uninsulated suspended floors are not suitable for use with ceiling heating, since they allow too great a heat loss, as well as the risk of discomfort from cold feet. Large single glazed areas may produce locally unsatisfactory conditions, either from 'radiation draughts' or downdraughts.

4 CONCLUSIONS

This series of experiments has investigated the reactions of people to overhead heating, generally from a heating panel extending over the ceiling. A measure of asymmetry has been developed, termed the v.r.t.

A vector radiant temperature of 20K does not increase the mean discomfort vote. However, this level of radiation is noticeable, and may be blamed for causing discomfort. It is recommended that for normal indoor situations a v.r.t. of 10K be regarded as the upper limit. There is no difficulty in meeting this criterion in well insulated buildings, but buildings with poor insulation and large windows may require further insulation to reduce the power loading.

There is evidence to suggest that the direction of the radiation is important. Cold radiation on the back and warm radiation on the face are apparently disliked.

APPENDIX 1

The Thermal Radiation Field

It rapidly became apparent in the early stage of this work that a major factor hindering the understanding of directional radiation was the lack of any common system of units. Experimenters invented their own units to measure asymmetry, used each other's units inaccurately, or abandoned any attempt at generalisation and simply recorded the ceiling temperature used. At Capenhurst we borrowed the concept of the radiation vector from illumination theory, and extended it for use in thermal radiation work. A formal theory of the thermal radiation field was later developed and published.[10] This allows the radiation at a point in space to be described in any required detail. For the purpose of predicting comfort reactions, it is sufficient to use two quantities, a scalar quantity describing the total amount of radiation (mean radiant temperature) and a vector quantity (radiation vector) describing the strength and direction of the radiant asymmetry. Comparison is easier if the radiation vector is expressed in the same units as mean radiant temperature; this is done by converting it into the vector radiant temperature which is in units of temperature.

Mean radiant temperature T_r (°K). This describes the 'warmth' of the radiation at the point in space of interest, termed the test point. A small sphere at a fixed arbitrary temperature placed at the test point will exchange energy by radiation with the surrounding surfaces. Now imagine a uniform spherical enclosure surrounding the sphere. If the radiation exchange is unaltered, the enclosure is at a temperature equal to the mean radiant temperature of the surroundings. The mean radiant temperature (m.r.t.) is a scalar quality, and a function of position. It may be measured using a globe thermometer[8] or, more accurately but less conveniently, by using a thermopile. For simple geometries it is possible to calculated the m.r.t. using the expression

$$T_r^4 = \frac{1}{4\pi} \Sigma \phi_i T_i^4$$

where the surroundings consist of surfaces of temperature T_i, subtending solid angle ϕ_i at the test point.

Before going on to define the vector radiant temperature it is convenient to define another concept.

Irradiance E (W/m^2). The irradiance is the total amount of thermal radiation falling on a small plane surface, expressed in units of power/unit area. It is a function of the position and orientation in space of the element. Note that it is not a measure of radiation exchange, but of total incident radiation. It is therefore independent of the temperature of the receiving surface. The term may be used to describe the contribution of a source to the total irradiance e.g. the "irradiance from the lighting system". There are dangers here; the irradiance from a small high temperature source will be independent of the conditions in the rest of the room, but the irradiance from a source such as a heated ceiling cannot be isolated in this way.

Plane radiant temperature T_{pr} (°K). The plane radiant temperature (p.r.t.) expresses the irradiance in units of temperature, making it easier to visualise. The p.r.t. is the temperature of a uniform hemisphere which produces the same irradiance as exists in the real environment. It is easily visualised as the "average" temperature of half of the room. It is a function of direction and position. It is related to irradiance by

$$\sigma T_{pr}^4 = E$$

Vector radiant temperature T_v (°K). If the plane radiant temperature is measured on opposite sides of a plane element, the difference between the two values is a measure of asymmetry along the normal to the element. If the measurement is repeated for different orientations of the element, it is found that there is a unique maximum. In this position the difference between the two plane radiant temperatures is the vector radiant temperature, which is a vector quantity with magnitude and direction; its components may be measured in orthogonal directions and combined using the rules of vector addition. The formal mathematical quantity corresponding to v.r.t. is the radiation vector R (W/m²)

$$T_v = R/(4\sigma T_r^3)$$

$$\simeq 0.17R \text{ at room temperature}$$

Measurement

The radiation vector, and hence the v.r.t., may be measured directly using a differential radiometer.[5, 7] This device uses two opposed plane collector surfaces; the surfaces are insulated from each other, so that any difference in irradiance on the two surfaces causes a temperature difference between them. The temperature difference drives a thermopile, and the voltage output is proportional to the radiation vector. Several commercial net radiometers are available[13].

Calculation of Plane Radiant Temperature

The calculation of p.r.t. will be described for the simple case of a hot panel of temperature T_1 which is parallel to the test element in an otherwise isothermal enclosure, see Fig 5. The test surface is horizontal, and the downward facing p.r.t. is simply T_2, where T_2 is the temperature of the walls and floor. The upward facing p.r.t. is given by

$$T_{pr}^4 = F_{p1} T_1^4 + F_{p2} T_2^4$$

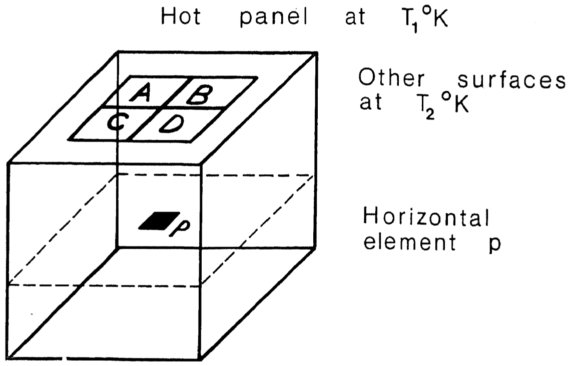
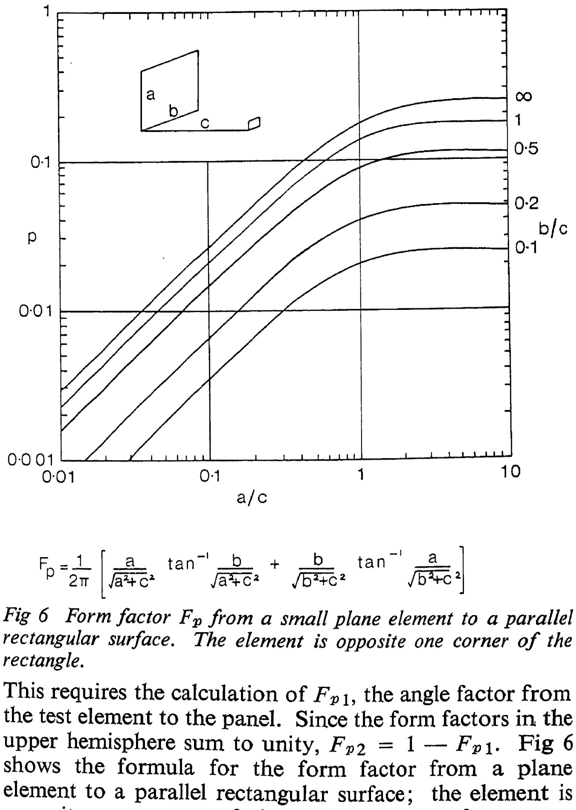


Fig 5 Room with heated panel on the ceiling. The form factor from the plane element p to the panel is calculated from

$$F_{p1} = F_{pA} + F_{pB} + F_{pC} + F_{pD}$$



$$F_p = \frac{1}{2\pi}\left[\frac{a}{\sqrt{a^2+c^2}}\tan^{-1}\frac{b}{\sqrt{a^2+c^2}} + \frac{b}{\sqrt{b^2+c^2}}\tan^{-1}\frac{a}{\sqrt{b^2+c^2}}\right]$$

Fig 6 Form factor F_p from a small plane element to a parallel rectangular surface. The element is opposite one corner of the rectangle.

This requires the calculation of F_{p1}, the angle factor from the test element to the panel. Since the form factors in the upper hemisphere sum to unity, $F_{p2} = 1 - F_{p1}$. Fig 6 shows the formula for the form factor from a plane element to a parallel rectangular surface; the element is opposite one corner of the surface. Form factors are additive, so F_{p1} can therefore be calculated as the sum of four components.

Example. It is required to calculate the v.r.t. at a point 2m below the centre of a heated ceiling of dimensions 3 × 3m, temperature 35°C. All other surfaces are at 18°C.

$F_{p1} = 4 \times F$ where F is to be found from Fig 6 with $a = b = 1.5$, $c = 2$. This gives $F_{p1} = 0.41$

$$\therefore \quad T_{pr}^4 = 0.41 \times (273 + 35)^4 + 0.59 \times (273 + 18)^4$$

$$T_{pr} = 298.3\text{°K i.e. } 25.3\text{°C}$$

Hence the v.r.t. is 25.3 — 18 = 7.3°C

If the room surfaces are at different temperatures, it becomes necessary to calculate form factors to all surfaces. This is most conveniently done by computer.

APPENDIX 2
SUMMARY OF ECRC EXPERIMENTS

Experiment A

Aim

To establish the degree of ceiling heating which causes discomfort.

Conditions

Four ceiling temperatures. Air and mean radiant temperature held fixed at a comfortable level.

	Condition Number: 1	2	3	4
Ceiling temperature (°C)	26.5	30	38	45
Wall temperature (°C)	26.5	25.5	20.5	15
Estimated v.r.t. (K)	0	6	12	20

Air temperature = 21°C, M.r.t. = 25.5°C

Design

24 male subjects, of which 8 were bald, experienced all conditions twice, once seated normally and once seated on a raised chair to simulate the effect of standing.

45 minute exposure.

Questionnaire

34 seven point scales.

Results

Subjects noticed directionality.

Comfort and other evaluative scales showed no change over the conditions. The subjects felt cooler in condition 4 (hot ceiling), even after shape factor corrections were made. Some effect of baldness and seat height on feelings of warmth of head.

Published as

Ceiling heating and comfort: I. ECRC/R463. December 1971. and: Subjective responses to overhead radiation. I. D. Griffiths and D. A. McIntyre, Human Factors, **16** (3), 415-422 (1974).

Experiment B

Aim

To find whether people are more sensitive to discomfort from overhead radiation in warm conditions.

Conditions

Two conditions, one uniform and one hot ceiling.

	Condition	
Ceiling temperature (°C)	26.5	45
Wall temperature (°C)	26.5	15
Estimated v.r.t. (K)	0	20

Air temperature = 25°C M.r.t. = 27°C

Design

16 male subjects experienced both conditions, in random order. Questionnaire after 40 minutes.

Questionnaire

34 seven point scales.

Results

The results agree with Experiment A. The mean Bedford vote was about 5 (comfortably warm). No discomfort was produced by the hot ceiling, but subjects voted that this condition was cooler.

Published as

Ceiling heating and comfort: II. ECRC/R475 1972.

Experiment C

Aim

Experiments A & B had found that subjects under a hot ceiling felt unexpectedly cool. This experiment compared subjective responses to horizontal, vertical and uniform radiation vectors.

Conditions

	Condition 1	2	3
Ceiling temperature (°C)	15	26.5	43
Wall temperature (°C)	29	26.5	19

Air temperature = 25°C, M.r.t. = 26.5°C

Design

Subjects experienced conditions in pairs, with the second following immediately after the first; 40 minutes exposure was allowed. The usual rating scales were used; in addition the subjects were asked to say which was warmer.

Results

Conditions 1 and 2 were perceived as having the same warmth. Condition 3 was cooler than either 1 or 2. Difference in sensation was 0.8 of an interval on the 7 point Bedford Scale, of which 0.3 can be explained by the shape of the human figure, which presents a larger area to horizontal than to vertical radiation.

Published as

Directional Thermal Radiation and Subjective Warmth. ECRC/N575 January 1973.

Experiment D

Aim

The previous experiments in this series had found that a v.r.t. of 20K under a ceiling of 45°C did not increase the discomfort vote. This experiment produced a v.r.t. of 20K using different panel sizes and temperatures, and the aim was to find out whether they produced different reactions. One condition was repeated, as a check on individual reliability, and a condition of high asymmetry was also included (See Table II).

Design

24 subjects sat under centre of heated panel for 40 mins, and then rated the environment on 28 seven point rating scales. Each subject attended all conditions.

Results

Condition 6 was clearly worse than the others. No other condition was worse than the control; in fact the medium panel (condition 1) produced significantly better results than the control. The control condition was not found to be warmer than condition 3 or any other, which fails to confirm the earlier experimental findings.

Published as

Subjective Response to Overhead Heating Panels of Different Size. ECRC/N679 December 1973.

Experiment E

Aim

The ECRC experiment had found no evidence of discomfort produced by asymmetric radiant environment with a v.r.t. of up to 20K. Some other work contradicted this, and suggested lower limits. This experiment modified the presentation of the conditions and the questionnaire, to check the findings of other workers.

Conditions

Four conditions, designed to produce equal feelings of warmth, were used. Air and wall temperatures were held equal to each other, and reduced as necessary to compensate for the raised ceiling temperature.

Table II Experiment D

		Conditions 1 Medium panel	2 Small panel	3 Hot ceiling	4 & 5 Control	6 Extreme
Panel size	(m)	1.3 × 0.6	0.25 × 0.06	3.6 × 3.6	–	0.25 × 0.06
Panel temp.	(°C)	80	550	45		700
Wall temp.	(°C)	20	20	20	27	15
V.r.t.	(K)	19	22	19	7	37
M.r.t.	(°C)	25	26	26	26	30
Air	(°C)	21	21	21	21	30

		Conditions			
		1	2	3	4
Ceiling temperature (°C)		23	30	38	45
Air & Wall temperature (°C)		23	22	21	20
M.r.t.	(°C)	23	24	24.7	25.6
V.r.t.	(K)	0	5	9	14

Design

Forty subjects experienced each condition, attending once only. After 15 min exposure, the subject was presented with seven rating scales which were always shown in the same order. The final two questions referred specifically to the ceiling heating, and asked it it was noticeable and if it caused any discomfort.

Results

All conditions produced the same warmth. Scales of general evaluation showed the warm ceiling condition to be preferred. However, the final scales showed the overhead radiation to be noticed and to be blamed for discomfort. It was concluded that the safe level of v.r.t. should be limited to 10K.

Published as

Sensitivity and discomfort associated with overhead thermal radiation. ECRC/N751 August 1974, and Ergonomics. (to be published)

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Reports referred to as ECRC may be obtained from the Electricity Council Research Centre, Capenhurst.

Institution Matters *Continued from page 225*

MEMBERSHIP APPLICATIONS

The undermentioned applications for admission to various grades of membership have been received and will be considered by the Committee not less than one month subsequent to this issue of the 'Journal', during which time any Fellow or Member may communicate by letter to the Secretary for the confidential information of the Committee any particulars he may possess respecting the qualifications or status of any candidate.

LA-KALAMCHI, Adan A. Wahab. Air-Conditioning Engineer with Directorate General of Civil Aviation, Baghdad, Iraq. Proposed by Prof. D. Probert; seconded by N. S. Billington.

BAILEY, David Anthony. Assistant Chief Electrical Engineer with Department of Architecture, Borough of Sunderland, Tyne & Wear. Proposed by D. Jackson; seconded by F. M. Owsnett.

BRADSHAW, Ian Ralph. (Trans L-Assoc) Environmental Engineer with Metropolitan Borough of Bury, Bury, Lancs. Proposed by G. M. Roberts; seconded by J. H. Bintliff.

CALDER, Laurence. (Trans L-Assoc) Technician Engineer with The City of Edinburgh District Council, Department of Architecture, Edinburgh. Proposed by E. P. MacFie; seconded by J. D. Manderson.

CHAN, Sun-Yen. (Trans Assoc-M) Mechanical Engineer with Swire Construction Services Ltd., Hong Kong. Proposed by S. C. Wong; seconded by K. M. Wong.

CLARK, David William. (Trans S-M) Building Services Engineer with Robert Matthew, Johnson-Marshall & Partners, London. Proposed by A. J. K. Reid; seconded by A. R. E. Northcott.

CRANHAM, Norman Cecil. (Trans L-Assoc) Senior Lecturer with Hertfordshire College of Building, St. Albans, Proposed by P. F. Brasier; seconded by J. W. Barnard.

DAVIES, Brynmor. Chief Mechanical/Electrical Engineer with Chief Architect's Department, Wakefield Metropolitan District Council, Wakefield. Proposed by F. Wild; seconded by G. M. Bell.

DAVIES, Philip James. Senior Heating Technician with Clwyd County Council, Mold, Clwyd. Proposed by R. J. Tooth; seconded by G. L. Jones.

DUCKWORTH, John William. (Trans L-Assoc) Project Technician with Raymond Allington & Associate, Nottingham. Proposed by R. Allington; seconded by M. P. Drayton.

DYER, Richard William Frederick. (Trans L-M) Building Services Design Engineer with Norman & Dawbarn Associate, Guildford. Proposed by R. S. Willcox; seconded by J. D. Jarman.

EVANS, Michael Rees. Professional & Technology Officer III with Property Services Agency, Department of the Environment, Cardiff. Proposed by W. C. Wride; seconded by J. N. Oliver.

FERNANDO, M. P. K. Heating Engineer with Peterborough Development Corporation, Peterborough. Proposed by R. C. Abraham; seconded by P. A. D. Jenks.

FLETT, Robert Alexander. (Trans M-F) Consulting Engineer with Alexander Flett Associate, Edinburgh.

FUNG, Edgar Francis. (Trans G-M) Professional & Technical Officer Grade I with Department of Health & Social Security, London. Proposed by K. N. Nightingale; seconded by R. Bacon.

GRAY, Kenneth Miller. (Trans G-M) Mechanical Services Engineer with Robert Matthew, Johnson-Marshall & Partners, Edinburgh. Proposed by G. H. Ward; seconded by W. C. Pyle.

GREGORY, Peter William. Assistant Engineer with Crown House Engineering Ltd., Southampton. Proposed by A. M. Gosnell; seconded by D. A. Jenkins.

HILTON, Kevin. (Trans L-Assoc) Section Engineer with Greater London Council, London. Proposed by G. McClelland; seconded by M. Taylor.

HOMAN, Philip. (Trans L-Assoc) Senior Heating Engineer with Sayes; & Co. Ltd., Pudsey, Yorks. Proposed by J. Sayes; seconded by B. Rodgers.

HUGHES, David Frederick. (Trans S-Assoc) Design/Development Engineer, Department of Education & Science, London. Proposed by L. E. J. Piper; seconded by G. C. Bailey.

HURLEY, Joseph. Engineer with Mott, Hay & Anderson, Croydon, Surrey. Proposed by T. H. Cosens; seconded by P. C. McLean.

KUMARASINGHE, Katunayake. A. C. (Trans L-M) Design Engineer with Leslie Doe Consulting Engineer, London. Proposed by L. N. Doe; seconded by B. G. Lawrence.

LADD, Alan Reginald. (Trans M-F) Divisional Director with Matthew Hall Mechanical Services Ltd., London.

LEE, Eddie Ho-Kai. (Trans L-Assoc) Mechanical Inspector with Electrical & Mechanical Office Fanling Depot, Public Works Department, Hong Kong, Proposed by S. P. W. Wong; seconded by T. H. Szeto.

LEIGH, John Frederick. (Trans S-Assoc) Section Leader Sulzer Bros. (UK) Ltd., Manchester. Proposed by G. K. Faulkner; seconded by B. Mills.

LEUNG, Chi Keung. Mechanical Maintenance Engineer with Hong Kong Electric Company, Ltd., Hong Kong. Proposed by H. P. Kwong; seconded by Y. T. Ip.

LOTERYMAN, Federico. Senior Engineer with Donald Smith, Seymour & Rooley, London. Proposed by R. H. Rooley; seconded by E. L. Hunt.

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MITCHELL, Roger William. (Trans S-Assoc) Resident Mechanical Engineer with Watford Borough Council, Watford, Herts. Proposed by B. Foweather; seconded by R. K. Khosla.

MUSA, Erdogan Hussein. Acting Senior Building Services Engineer with Building Services Branch, Public Works Department, Hong Kong. Proposed by P. K. Kwok; seconded by W. K. Lee.

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PANKHIDA, Yousef. Senior Design Engineer with Lindsell Dewell & Co. Ltd., Hainault, Essex. Proposed by E. Krajewski; seconded by D. Hopper

PATTERSON, Samuel. (Trans S-Assoc) 3rd Engineer, Energy Sales with Northern Ireland Electricity Service, Belfast. Proposed by H. G. Wilson; seconded by T. C. Jackson.

PICTON, Michael Phillip. (Trans L-Assoc) Design Draughtsman with Department of the Environment, Portsmouth, Hants. Proposed by N. Shaw; seconded by D. J. Webster.

PRITCHARD, George Edward. Standards and Consulting Engineer with British Steam Specialties Ltd., Leicester. Proposed by J. W. Coe; seconded by A. Hoggar.

PYBUS, Fred. Professional & Technical Officer, Grade I with Department of Health & Social Security, London. Proposed by A. Smith; seconded by D. Stradwick.

SHINDLER, Kenneth. Associate with Pashler & Partners, Birmingham. Proposed by J. P. Sandison; seconded by G. W. Jetson.

SIMONDS, Frederick. (Trans M-F) Director with Bridgwater Technical Services, Bridgwater, Somerset.

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STEWART, Alexander William Kerr. (Trans M-F) Professor and Head of Department of Environmental Engineering, University of Strathclyde, Glasgow.

TANG, Chow-Keung. Assistant Building Services Engineer with Housing Department, Housing Authority Headquarters, Hong Kong. Proposed by K. M. A. Lee; seconded by Y. W. Wan.

VARLEY, David. (Trans L-Assoc) Deputy Chief Engineer with Yorkshire Post Newspapers Ltd., Leeds. Proposed by G. Shepherd; seconded by M. A. Naylor.

YOULE, Anthony. Lecturer in Environmental Control with School of Architecture, Portsmouth Polytechnic, Portsmouth. Proposed by M. J. Green; seconded by K. A. Turl.