ECR/R1446

ELECTRICITY COUNCIL RESEARCH

ECR/R1446

THE ELECTRICITY COUNCIL
30 MILLBANK LONDON SW1P 4RD

A STUDY OF LARGE AIR TO AIR HEAT PUMPS IN A CLOTHING STORE

Environmental Engineering Section

Job No. 9/749

May, 1981

A STUDY OF LARGE AIR TO AIR HEAT PUMPS IN A CLOTHING STORE

SUMMARY

This report describes the field trial undertaken at a Manchester clothing store with a gross floor area of 5950 m^2, served by eight rooftop air to air heat pumps. The heat pumps have a design heat output of 61 kW each, and the data complements that which has been derived from earlier trials with smaller units.

A description is given of the store and its services, with the instrumentation installed. Detailed instrumentation was applied to one representative floor, and the overall pattern for the store derived using this data and the known total loads and operating hours. The energy consumptions are shown for a period of one year, with typical demand curves and the annual running costs.

The information obtained is discussed with reference to previous heat pump field trials and to field trials carried out in two other stores in the same chain employing central plant air conditioning and oil heating. It is shown that the total electrical energy was similar at Manchester to the other stores, but that the heating energy was considerably lower, due to the lower specific heat requirement. The predominant requirement was for cooling, which in the winter months is satisfied by free cooling.

Coefficients of performance for the heat pumps were found to be similar or slightly lower than others previously measured with a seasonal heating COP of 2.3 - 2.4. The importance of maintenance was highlighted by one of the eight heat pumps whose performance was observed to fall off under a fault condition, yet without the machine tripping out.

Attention is drawn to the distribution energy for the store, which at 68.6 kWh/m^2 per annum contributed 35% of the electrical energy, and which it is felt could be reduced if a different approach to ventilation design were adopted.

Running costs for the store totalled £6.70/m^2 for the year July 1979 to June 1980.

A STUDY OF LARGE AIR TO AIR HEAT PUMPS IN A CLOTHING STORE

CONTENTS PAGE

A STUDY OF LARGE AIR TO AIR HEAT PUMPS IN A CLOTHING STORE

1 INTRODUCTION

Since 1975 the performance of packaged air to air heat pumps has been monitored in a number of buildings with differing uses and constructions. The findings of the field trials are the subject of the reports listed as References 1 to 5.

The heat pumps monitored were manufacturers' standard production units, which were found to operate with seasonal Heating Coefficients of Performance of the order of 2.5. Whereas at the time of the earlier trials the largest units had outputs in the region of 30 kW, much larger units are now available of three to four times the size. It was considered that comparative data should be obtained on some larger single piece heat pumps, and the opportunity was therefore taken to install instruments in a new four storey clothing store in Manchester, served by eight such machines.

In addition to obtaining data on the heat pumps, it is also possible to draw comparisons with two other stores in the same chain which were the subject of the report ECR/R808. These were air conditioned, with heating from oil fired boilers, and energy comparisons may be made using heat pump COP_H and oil boiler efficiency figures.

2 BUILDING DESCRIPTION

2.1 General

The store is situated in a very large modern shopping centre containing shops of varying sizes entered from the covered pedestrian malls. It comprises four floors; Basement, Lower Mall, Upper Mall and Upper Service Levels. The sales areas take up the greater part of the upper three levels and a smaller portion of the basement, which also has administration areas, kitchen, stockroom, unloading bay and staff rooms. The store has entrances from the Lower and Upper Malls, and also from the street at the Lower Mall level. Figure 1 shows the floor plan of the Upper Mall level.

The gross floor area is made up as follows:-

	m^2
Basement - sales	680
Basement - other	950
Lower Mall	1480
Upper Mall	1420
Upper Service	1420
Store Total	5950

2.2 Building Services

2.2.1 Heat Pumps

Heating and cooling for the store is provided by eight air to air heat pumps, mounted on the roof of the building. Figure 2 shows the general lay-out of a heat pump. Each unit features two compressors and four outdoor fans. Twin centrifugal fans driven from a single motor provide the indoor air, which returns via a mixing section with recirculation, exhaust and fresh air dampers. An automatic roll filter is incorporated. A further feature is that the exhaust air is expelled below the outdoor coils, which is calculated to give an increase in heating COP and a reduction in defrosting. An emergency direct electric heater is fitted at the supply air outlet.

Each floor is served by two heat pumps, operated together except in the basement where one unit serves the sales area and the second the administrative area. The air travels via ducts to the ceiling voids, and is then blown into the conditioned areas by 'Envirolator' fan-powered diffusers. There are seven 7.5 kW return air fans in the Upper Service level ceiling at the head of builder's work return air ducts. These operate with each heat pump supply fan except that for the basement administrative area, whose services are more fully described in Section 2.2.3.

The manufactuers' data for heat pumps No 5 and 6, serving the Upper Mall, which were the subject of detailed measurement as described later, are given below.

Refrigerant	R-22
Cooling Capacity	81 kW at 29.4°C
Heating Capacity	61 kW at 1.7°C
Direct Heater (Stand by only)	25 kW
Indoor Fan Air Volume (nominal)	14000 m^3/h
(as Commissioned)	13592 m^3/h (HP 5) 14187 m^3/h (HP 6)
Current Starting	250 amps/phase
Running	85 amps/phase

2.2.2 Heat Pump Control

The overall running period of the heat pumps is determined by a timeswitch with day omission. A step control is used to give a staggered start over the eight units. The same control brings into operation the powered ceiling diffusers and return air fans. There is no automatic variation of the start time, but seasonal adjustments are made manually.

On each floor except the basement, the heat pumps are operated in pairs using one step controller with a room temperature detector, each step controller having nine switching operations. There are four heating and four cooling stages, whereby between one and four heat pump compressors are running according to demand, and a central switch operating the reversing valves.

In addition to the step controller, there are two outside thermostats set at 5°C and 12°C, which operate to open the fresh air dampers for free cooling between these ambient temperatures, when the step controller calls for cooling. During free cooling, the compressors are prevented from operating, and above the set ambient, mechanical cooling occurs with the dampers at the normal position. There is no additional control to close the dampers to the outside air during preheating.

The emergency heater battery fitted to each heat pump can be brought in only by a key switch which also disconnects the supply to the heat pump compressors. When in use, the heater batteries operate through the same step controller as the heat pump compressors.

The basement heat pumps operate separately but with similar controls.

2.2.3 Other Items of Plant

In the basement is located a gas fired boiler rated at 102 kW supplying LPHW to various heating coils in the basement. As the area other than the sales area is subdivided, with overall heat pump control from a temperature detector in the staff dining room, there is a need for local modulation. This is accomplished by using reheating coils in the supply air, which are controlled by local room thermostats operating diverting valves in the water pipes. The boiler water is also used for entrance warm air curtains, and for heating the stockroom.

Other than the main air supply, there are additional kitchen and basement extract fans, a stockroom supply fan and several small extract fans for service rooms such as the lift motor room. The additional fan load amounts to approximately 15 kW.

Domestic hot water for the kitchen, toilets and cleaners' room is provided by five local electric water heaters, the smallest being 3 kW and 34 litres the largest 9 kW and 227 litres. The total electrical load is 21 kW.

The kitchen houses electric catering equipment rated at a total of 49.75 kW. The lighting in the store gives 600 lux to the sales area, from an installed load of approximately 25 W/m^2.

2.3 Design Conditions

The design conditions for the store are as follows.

	Summer	Winter
Sales	21°C db 50% RH	21°C
Administration	21°C db 50% RH	21°C
Stock	20°C	20°C
External Ambient	26.6°C db 18.9°C wb	-1.1°C saturated

2.4 Heating and Cooling Loads

As is discussed later, the store was considered from the particular point of view of one floor, the Upper Mall, and also as an overall envelope. The heating and cooling loads considered in this manner are as given below.

The fabric U values in $W/m^{2}{}^{o}C$ are;

Walls	0.85	(concrete and lightweight block cavity wall, with tile facing)
Roof	1.2	(concrete, decking, screed and asphalt)
Glazing	5.6	(single glazing)

The design fresh air supply is;

Upper Mall 7,400 m^3/h

Total Store 30,800 m^3/h

Peak customer occupation 1500 people

Winter design heat loss:-

		kW
Upper Mall	Fabric	6
	Ventilation	54
	Total	60 (42.3 W/m^2)
Total Store	Fabric	80
	Ventilation	224
	Total	304 (51.1 W/m^2)

3 MONITORING PROGRAMME

3.1 Duration and Scope

The store was opened in November 1978 and instrumentation was installed at this time. There were during the first winter certain teething troubles and it was agreed to omit data from the early period as it would be untypical. For this report, the data for the latest period covered is used, this being the year July 1979 to June 1980.

For a building of this size the requirements for instrumentation would be extremely large if all items were monitored. At the outset therefore the field trial policy was to obtain a broad overall picture, with more specific data for one floor, which was decided as the Upper Mall. In the final analysis, the data for one floor could then be interpreted to give an overall picture, although certain details would be subject to estimation.

3.2 Instrumentation

Electrical metering was installed as shown in Figure 3. Three kWh contact meters were used, each connected to a magnetic film demand recorder, from which half hourly demands could be derived. The loads measured were the two heat pumps serving the Upper Mall, and the lighting and small power for this floor. The total load for the shop was monitored using the day/night NORWEB tariff meters.

Hour run meters indicated the running time of the two compressors in each heat pump. A multipoint temperature recorder was installed with measurements taken, for each Upper Mall heat pump, of return air, mixed air onto and off the indoor coil, and delivered air temperature. External ambient temperatures were obtained from the Manchester Weather Centre, which is close to the store. The air temperature within the Upper Mall sales area was monitored using a thermograph.

During the course of the field trial it was decided that some additional detail should be obtained on the heat pump operation. An event recorder was installed on 14 November 1979, showing for each of the two heat pumps the operation of the compressors, reversing valves and free cooling. This enabled the hours spent in the different heating and cooling modes to be accurately derived. Previous to this the information could be obtained from the temperature recorder, but with greater difficulty and less accuracy.

3.3 Metered Electrical Energy

Table 1 shows monthly energy consumptions for the metered loads for a period of one year. Also shown are the kW demands at the time of the Upper Mall level maximum demand each month. Table 2 shows these figures expressed per m^2 related to the gross floor area associated with the load.

The day/night energy split was obtained for the heat pumps, lighting and power of the Upper Mall level from the magnetic film demand recorder printouts. The total shop day/night energy split was obtained from NORWEB tariff meters and as shown on Table 3 very little night energy is used. Energy consumptions for the indoor fans of both heat pumps have been obtained from the magnetic film demand recorder printouts and are given below:

	Indoor Fan	
	kWh	kWh/m^2
Heat Pump 5	19,900	14.0
Heat Pump 6	16,900	11.9
Total	36,800	25.9

3.4 Other Calculated Energy for Upper Mall

The return air fans associated with the two heat pumps were not metered. From the known rating and the hours run which are common to the heat pumps and return air fans, the annual consumption of the return air fans was calculated to be 41,500 kWh, 29.2 kWh/m^2.

Similarly, the consumption of the Envirolator fans for the floor was calculated at 19,800 kWh, 13.9 kWh/m^2.

The total annual energy for the Upper Mall was therefore made up as follows:-

	kWh	kWh/m^2
Heat Pump Compressors and Outdoor Fans	38,254	26.9
Heat Pump Indoor Fans	36,800	25.9
Return Air Fans	41,500	29.2
Envirolator Fans	19,800	13.9
Lighting and Small Power	101,214	71.3
Upper Mall Total	237,568	167.2

It may be seen that fan energy comprises a large proportion of the whole, being 72% of the heating and ventilating load and 41% of the Upper Mall total.

3.5 Total Shop Energy

Apart from the electrical energy, which for the whole shop totalled 1,135,410 kWh, or 190.8 kWh/m^2, there must be included the gas boiler consumption. This is not available on a periodic basis, but returns for the year show a total consumption of 3457 therms, equivalent to 101,290 kWh before any efficiency adjustment. If a boiler efficiency of 65% is assumed, the equivalent electric energy is 65,840 kWh, 11.1 kWh/m^2.

For the breakdown of the total electrical energy, estimates must be used based on known loads and hours run, and using data from the Upper Mall where relevant. In this manner the composition of the total is calculated to be approximately as follows:

	kWh	kWh/m^2
Lights and Small Power	390,000	65.5
Heat Pump Compressors and Outdoor Fans	162,000	27.2
Heat Pump Indoor Fans	147,000	24.7
Return Air Fans	145,000	24.4
Other Fans	36,000	6.1
Envirolators	80,000	13.4
Escalators and Lifts	145,000	24.4
Kitchen	21,000	3.5
Miscellaneous	9,410	1.6
Total	1,135,410	190.8

3.6 Demand Profiles

Figures 4 to 8 show demand profiles for the Upper Mall loads for five days representing winter and summer patterns. The profiles show a steady lighting load throughout the day, of 34 - 35 kW summer and winter, but considerable variation in the heat pump load.

In Figures 4 and 5 , for cold winter days, there is a high initial demand for the heat pumps which falls off when occupational gains take effect. Figure 4 shows a second heating peak for heat pump 6 in the late afternoon while Figure 5 shows a small peak in the afternoon for heat pump 5.

Figures 6 and 7 show the demand profile of two hot days. In Figure 6 a flat profile for the heat pump is obtained, indicating a steady cooling load throughout the day. Figure 7 shows a steady cooling load during the later part of the day only. This is due to the ambient temperature in the morning having been lower. For a mild day, Figure 8 shows an initial heating peak for the two heat pumps which disappears rapidly.

The characteristic which is most noticeable on the load curves is that the morning heating peak occurs at such a time as to overlap the lighting and and power load. Only Figure 5 shows the heat pump peak before that of the lighting. While the loads for the whole store cannot be analysed in the same manner, it may be assumed that the patterns of the other floors are very much the same, since they are controlled in sequence. The resultant pattern for the whole store would therefore have a significant morning peak in winter. From considerations of the electricity demand charges, the load would benefit if the preheating time of the heat pumps was a little earlier, such that there was a reduced overlap with the lighting. Besides benefitting the maximum demand, this would place more energy consumption within the night period and make better use of the day/night feature. It can be seen from Table 3 that the use of night rate electricity was small.

3.7 Internal Temperature

Figures 9 and 10 show the thermograph traces for the Upper Mall sales floor at differing ambient temperatures. On winter days no difficulty was experienced in achieving comfort temperatures quickly and maintaining them. Control was generally good, with any irregularities usually being in the form of a small temperature rise due to heat gains before cooling came on. Saturday afternoons in particular showed evidence of this. During the unoccupied periods the temperature fell no lower than 17°C, evidence of the considerable mass of the building structure.

The thermograph for 18 - 25 June 1979 shows the internal temperature maintained at 23 - 24°C with 27°C ambient. This is above design but it is known that one of the heat pumps was faulty at this time and had a reduced output. The following thermograph for 21 - 28 July 1980 shows a more clearly defined cooling characteristic, with control at around 22°C. The 1980 summer did not however provide any sustained hot weather to test the system to the full, there being only one occasion from May to August when design ambient was reached, and only ten short daily peaks over 23°C. Internal relative humidity was not measured.

Details of the monthly average daytime (0800 hours - 1800 hours) temperatures are given in Table 4.

3.8 Coefficient of Performance (Heating)

The coefficients of performance of the heat pumps may be determined from the heat output, given by the airflow and the temperature difference across the indoor coil, and the electrical input given by the demand recorder. In order to be able to relate these two correctly, it is necessary to use periods when the heat pump is running in the same mode for at least an hour. The better data in this respect is usually obtained during the early hours of the day, since the later operation is frequently cyclic. The amount of data which can be obtained for the milder weather is usually less for the same reason.

Coefficients were calculated for both heat pumps on one and two stage operation. As has previously been the practice, the indoor fan heat was omitted from both the output and input. For single stage operation, because only half of the indoor coil is used, considerable temperature variations occur across the supply air stream. Although average readings were taken, it was not found possible to achieve entirely consistent results, and some measurement error is therefore present. Consistent readings were found on two stage operation. Defrosting was not monitored and the COP_H figures make no allowance for defrosting.
Figures 11 and 12 show plots for each of the heat pumps 5 and 6 for one and two stage operation. The better results were obtained for heat pump 6, where the two stage COP_H ranged from around 2.4 at $-1^{\circ}C$ design ambient, to nearly 3.0 at higher ambients. On single stage operation, the results show a considerable degree of scatter, for the reason previously noted, but the indication is that the single stage COP_H was in the order of 20% down on the two stage COP_H. The manufacturers do anticipate a lesser COP_H on single stage operation, due to a higher proportion of outdoor fan energy. From the known fan ratings this may give an 8% - 10% reduction.

The results from heat pump 5 were not so good on two stage operation, with the COP_H ranging from 1.9 to 2.6. On single stage operation the figures were very poor indeed, and a fault condition was obviously present. It may be mentioned at this point that this machine gave more problems than any of the other seven, with a number of refrigerant leaks occurring, reducing the output. Its operation could not be considered to be normal during the major part of the field trial and therefore the performance of heat pump 6 must be taken as representing the correct operating characteristic.

3.9 Coefficient of Performance (Cooling)

Figure 13 shows the cooling COP of heat pump 6 for summer 1979, which averaged approximately 2.3. No data was available on heat pump 5 for this period, as in the absence of an event recorder at this time the periods of cooling were difficult to pick out. Such data as could be distinguished indicated lower temperature differences than for heat pump 6, and it is clear that the cooling performance was equally suffering from the problems mentioned in 3.8.

At the end of the field trial, in the early summer of 1980, heat pump 5 appeared finally to be cured of its problems and a small amount of further cooling data was obtained, as shown in Figure 14, with data also for heat pump 6. This indicates that the performance of the two machines was then very similar.

3.10 Operating Pattern

Table 5 shows for each of the Upper Mall heat pumps the hours of operation in different modes throughout the year. The compressor run figures are derived from hour counters, and the others from the temperature recorder or, from November, the event recorder. The accuracies of different recording methods differ, and there are therefore some small discrepancies, although the overall pattern is clear.

The hours of heating, mechanical cooling and free cooling follow seasonal patterns of a form which would be expected. Heating is confined almost entirely to the months of October to April, and the majority of mechanical cooling occurs between April and October, there being some Spring and Autumn overlap. The cooling requirement continues throughout the year, being satisfied in the winter months by free cooling alone.

The figures in Table 5 indicate generally the greater demand for cooling than heating, which could be seem in more detail from the daily records. As the load curves of Figures 4 and 5 show, even in design winter weather the heating requirement dropped sharply during the morning, and only occasional later heat inputs were needed. Free cooling frequently occurred in the later part of the day in winter, this being particularly noticeable on Saturdays, when peak occupation might be expected.

3.11 Running Costs

The building operates on the Norweb Maximum Demand Seasonal Tariff with a day and night feature, night rate being applied between 00.30 and 07.30 GMT. Table 6 shows the costs for the year July 1979 to June 1980, as billed. At the end of the year the rates in force were as follows.

Day Units	2.66p/kWh
Night Units	1.25p/kWh
Fuel Adjustment	0.00043p/penny fuel cost over £35/tonne. (0.1p at June 1980)
Demand	April to October - Nil November to March £2.85/kW
Power Factor	Demand charge will be increased by 1% for each complete 1% by which the power factor is below 90%
Service Charge	£0.45/kVA of supply capacity.

In Table 6 costs are shown in £ and £/m^2 of floor area. The total for the year was £37,734, or £6.34/m^2.

The running cost for the gas boiler was £848, or £0.14/m^2.

4 DISCUSSION

4.1 General

The information obtained in this field trial can be viewed from two aspects. Firstly it provides evidence of the performance characteristics of these large single piece heat pumps, This may be examined alongside that which was obtained from previous field trials, full details of which may be found in the listed references.

Secondly, the integration of a heat pump system into a store of this size may be evaluated in terms of the total energy and running cost parameters. In this respect comparisons may be made with the two stores in the same chain, at Exeter and Bromley, which were the subject of the report ECR/R808, Reference 6.

4.2 Heat Pump Performance

4.2.1 Maintenance of Performance

It is unfortunate that of the eight heat pumps serving the store, one of those monitored in detail, serving the Upper Mall, had a poorer reliability record than all the others. For the six heat pumps not monitored, as far as can be judged the better performance of heat pump 6 is typical. In this respect the service records indicate that heat pump 5 was indeed the odd machine out in the attention required.

As a first comment however, it is appropriate to emphasise the possibility that the performance of a heat pump can be below specification without necessarily causing any safety or alarm mechanism to operate. In such circumstances the condition could in many installations continue unnoticed until such time as the peak capacity is required, when the fall in output may be felt. This could in practice represent a lengthy period of time.

While in any heat pump installation the importance of regular maintenance cannot be too strongly emphasised, the increased running cost represented by any drop in performance becomes more significant with a large unit. It is suggested therefore that a valuable contribution could be made by equipment enabling the main operating parameters to be checked quickly by in-house maintenance staff, between full service visits. For a small heat pump, the capital cost would probably be too high, but with the larger units it would be proportionately less.

With heat pumps finding an increasingly large market, any opportunity for development on these lines should be pursued fully.

4.2.2 Coefficient of Performance

The coefficients of performance of the two machines monitored were considerably different. As previously stated, heat pump 6 was the one working correctly, and COP's were found of a similar order to those for previous heat pumps. The values for heat pump 6 can therefore be taken as typical of the others used here. For this machine, a COP_H of between 2.4 and 2.9 was found for two stage operation from $-1^{\circ}C$ to $12^{\circ}C$ ambient. Due to the difficulties of measurement the single stage figure is less accurate, but a range of 2.0 - 2.4 was indicated here. These figures exclude the effect of defrosting which was not separately monitored, as previous experience has shown it not to be of major significance, and enables us to estimate its value.

Referring to previous reports, COP_H figures for smaller packaged heat pumps have been in the range (2.0 - 2.2 to 2.7 - 3.1) over a similar ambient temperature range, and including the effect of defrosting. The effect of defrosting has been to reduce the basic COP_H at $-1^{\circ}C$ ambient by up to 0.4 to 0.5, while at $12^{\circ}C$ defrosting is no longer required. Therefore, the COP_H of these larger heat pumps was somewhat similar on two stage operation to those previously monitored, and slightly lower on single stage operation. The expulsion of exhaust air below the outdoor coils did not show any significant benefit.

Over a season, as Table 5 indicates, there are more hours of operation on single stage than two stages. Weighting the COP_H in accordance with this, and the proportion of usage at different ambient temperatures, gives a calculated seasonal COP_H of between 2.3 and 2.4.

On cooling, a COP in the range 2.6 to 2.0 was measured for ambient temperatures of $12^{\circ}C$ to $24^{\circ}C$, taking the compressor and outdoor fan energy input. For the compressor only, which is often the quoted figure, the COP would be 2.85 to 2.6. The additional unmeasured latent cooling could be expected to add 20% to these figures, giving a maximum of around 3.4. This would be comparable to the typical quoted performance for a large chiller.

4.3 Free Cooling

It is clear from the operating pattern shown in Table 5 that the cooling requirement of the store is a year-round one, and that cooling use exceeds heating. Of particular interest is the use made of the free cooling facility.

For the Upper Mall, each heat pump operated in the free cooling mode for a total of 377 hours during the year. It is calculated that the cooling effect provided by the fresh air would have required electrical energy totalling 5500 kWh if produced mechanically. At the present unit cost of 2.77 p/kWh plus fuel variation this represents a saving of £166 a year for each machine.

As described in section 2.2.2, the free cooling operates under the control of a step controller linked to a space temperature detector, but within ambient temperature limits set by external thermostats. While there is an external temperature above which free cooling alone cannot meet the cooling demand of the building, this does not necessarily imply that the fresh air can no longer be used. In terms of sensible heat, the external air has a reducing cooling capacity until the desired space temperature is reached. High humidity can reduce the useful range, but there remains a band wherein free cooling and mechanical cooling could operate together with good effect, saving electrical energy. The recorded savings due to free cooling could therefore possibly be enhanced given a control sequence allowing some simultaneous operation.

In certain buildings, such as the school reported in ECR/R1434, it can be concluded that with the cooling load confined to the summer months, when the cooling potential of the outside air is restricted, free cooling is so little used as to be uneconomic. In this instance where cooling is required in all months, there is a greater measurable benefit, although still not large as a percentage of the total building energy. On the basis of the Upper Mall, the total savings would be 7.4 kWh/m^2 or £0.22/m^2, in a total of 190.8 kWh/m^2.

In providing free cooling, additional capital expenditure is required, to supply and control the necessary volumes of air. For any installation, therefore, the anticipated running cost benefit should be compared with the additional capital costs involved, knowing the pay back period required from the expenditure, and also allowing for fuel cost inflation over the period.

4.4 Building Energy

From sections 3.4 and 3.5, the total electrical energy for the Upper Mall was calculated at 167.2 kWh/m^2, excluding lifts and escalators. Including these items, and the kitchen and miscellaneous loads, the total for the store was 190.8 kWh/m^2. Gas added 11.1 kWh/m^2 electrical equivalent assuming a 65% boiler efficiency.

Referring to the earlier report ECR/R808, for two stores in the same chain, at Exeter and Bromley, the following comparison may be made.

	Manchester	Exeter	Bromley
Gross Area m^2	5950	2550	3240
Electricity Consumptions per annum kWh/m^2			
Lighting/Small Power	65.5	63.7	76.4
Air Conditioning and Heating Distribution	68.6	49.0	35.3
Cooling Plant	-	22.8	43.2
Heat Pumps (comp + o.d.f.)	27.2	-	-
Lifts/Esc./Kit/Misc	29.5	54.0	30.0
Total Electrical	190.8	189.5	184.9
Fossil Fuel Input	17.0 (gas)	137.0(oil)	182.0(oil)
Equivalent Elec. at 65% eff.	11.1	89.1	118.3

Looking at the figures above, it may be seen that the lighting and small power is of a similar order for the three premises. Distribution energy is greatest at Manchester and least at Bromley, but the figures for each shop are very much proportional to the installed loads. These are 25.6 W/m^2, 19.3 W/m^2 and 13.5 W/m^2 for Manchester, Exeter and Bromley respectively.

The cooling consumption is accurately known at the latter two stores as separate cooling was employed. The difference between the two can be attributed to the use of free cooling at Exeter, but not at Bromley. For Manchester, the heat pumps were metered in total, and the cooling use must be calculated. From the known hours run, the heating/cooling split is found to be 26% heating, 74% cooling, for the Upper Mall.

If this breakdown is taken as being representative of the whole store, then of the total compressor and outdoor fan energy of 27.2 kWh/m^2, the heating would be 7.1 kWh/m^2 and the cooling 20.1 kWh/m^2. The cooling would then be very similar at Manchester to that at Exeter, both stores employing free cooling. For heating, the Manchester figure is extremely low in comparison to the others.

This cannot be attributed to degree day differences, since the degree day figures for the appropriate periods are virtually identical at Manchester and Bromley, although the difference between Exeter and Bromley is proportional to their degree days.

There are however differences in the design heat requirements, which are 51.1 W/m^2, 98.2 W/m^2 and 92.3 W/m^2 respectively. The extent to which the heat requirement is offset by known gains is similar (between 53 and 57 W/m^2) in each case. The nett losses after taking off the fixed gains including fan heat are nil, 41.9 W/m^2 and 38.4 W/m^2 respectively. The basic heat losses at Exeter and Bromley are therefore approximately 1½ times that at Manchester, but the nett requirements show a completely different picture. Both the total building energy differences and the proportion supplied by the heating system can be attributed to these differing requirements.

Overall the building has shown a low energy consumption for heating which the known requirements and fixed gains would suggest. The cooling consumption has been similar to that experienced elsewhere, and free cooling has made a measurable contribution, which could probably be further improved with slight control modifications.

4.5 Distribution Energy

In the analysis of the total building energy, it was observed that the distribution energy was greater at Manchester than at Exeter and Bromley, due to the greater installed fan load. The use of a multiplicity of air movement equipment therefore gives a disadvantage in energy consumption. A system employing a simpler extract system, possibly incorporating a heat recovery coil, could show a better return. This would however require a different conceptual approach from the outset.

5 CONCLUSION

It has been shown that the predominant requirement in this store is for cooling, which in the winter months is satisfied by free cooling. Using heat pumps, the large fresh air requirements and mechanical cooling are satisfied, together with the heating, by single piece units, requiring no separate heating system except in a small area of the basement. Plantroom space is therefore minimised.

The multiplicity of air handling equipment gave a higher distribution energy than other stores, and this is seen as a disadvantage which an alternative design approach could obviate.

Measured heating coefficients of performance were similar to or slightly lower than those of smaller heat pumps previously monitored. Allowing for defrosting, a range of 2.0 to 2.9 was achieved on two stage operation. The seasonal COP_H was calculated to be in the range 2.3 to 2.4. For cooling, using for comparison the compressor only COP, up to 3.4 was found, similar to a large chiller unit. However, the performance was found to drop significantly under fault conditions which in the absence of monitoring equipment might not be quickly identified. The importance of operational checks and regular maintenance is strongly emphasised.

While the majority of observations were concerned with the heat pumps themselves and the building energy, space temperatures were found to be generally well controlled and close to design. Such departures from design as occurred in the first summer were the result of reduced performance of one machine which was later to be corrected.

The building energy totalled 190.8 kWh/m^2 per annum for electricity, plus the electrical equivalent of 11.1 kWh/m^2, assuming 65% efficiency, for gas. This total was considerably less than other stores in the same chain previously monitored, the design and situation of the building contributing to this. Overall running costs for the period July 1979 to June 1980 were £6.48/m^2. Free cooling contributed a saving of approximately £0.22/m^2, which is 3.4% of the total.

REFERENCES

1 The Performance of Packaged Heat Pumps in an Office Building. The Electricity Council, November 1977. ECR/R1105.

2 The Performance of a Packaged Heat Pump in a High Street Store. The Electricity Council, February 1978. ECR/R1127.

3 The Energy Consumption of a Heat Pump in a High Street Shop. The Electricity Council. January 1979. ECR/R1213.

4 The Performance of Heat Pumps in a Bank. The Electricity Council, July 1979. ECR/R1269.

5 The Performance of Packaged Air to Air Heat Pumps in a Primary School. The Electricity Council, March 1981. ECR/R1434.

6 A Study of the Building Energy Consumptions of Two High Street Self Service Clothing Stores. The Electricity Council, April 1975. ECR/R808.

		1979						1980						Total
		July	August	Sept	October	Nov	Dec	Jan	Feb	March	April	May	June	
Heat Pump 5	kWh	3116	3180	3844	3700	2960	2708	2900	2212	3984	4168	5824	5032	43,628
	kW*	24	21	30	34	34	30	30	27	27	34	35	34	
Heat Pump 6	kWh	3942	3424	2396	2652	2120	2284	2528	1596	2216	3152	3144	1972	31,426
	kW*	19	18	19	37	35	32	18	18	29	32	34	21	
Lighting and Power	kWh	7596	7944	7792	9888	7880	6926	7992	7716	9656	9728	9908	8188	101,214
	kW*	34	34	34	34	37	34	35	34	35	35	35	35	
Total Shop	kWh	89,410	88,790	88,870	105,830	86,100	80,650	101,130	85,940	106,130	106,830	109,810	85,920	1,135,410
	kW	480	480	460	460	470	430	460	420	470	460	500	480	

Table 1 Consumptions and Demands (* at time of MD on Upper Mall Level)

		1979						1980						Total
		July	August	Sept	October	Nov	Dec	Jan	Feb	March	April	May	June	
Heat Pump 5	kWh	2.2	2.2	2.7	2.6	2.1	1.9	2.0	1.6	2.8	2.9	4.1	3.5	30.7
	W*	16.9	14.8	21.1	23.9	23.9	21.1	21.1	19.0	19.0	23.4	24.6	22.5	
Heat Pump 6	kWh	2.8	2.4	1.7	1.9	1.5	1.6	1.8	1.1	1.6	2.2	2.2	1.4	22.1
	W*	13.4	12.7	13.4	26.1	24.6	22.5	12.7	12.7	20.4	22.5	23.4	14.8	
Lighting and Power	kWh	5.4	5.6	5.5	7.0	5.6	4.9	5.6	5.4	6.8	6.9	7.0	5.8	71.3
	W*	23.9	23.9	23.9	23.9	26.1	23.9	24.6	23.9	24.6	24.6	24.6	24.6	
Total Shop	kWh	15.0	14.9	14.9	17.8	14.5	13.6	17.0	14.4	17.8	18.0	18.5	14.4	190.8
	W	81	81	77	77	79	72	77	71	79	77	84	81	

Table 2 Consumptions and Demands (* at time of MD on Upper Mall Level) per m^2

	1979						1980						Total
	July	August	Sept	October	Nov	Dec	Jan	Feb	March	April	May	June	
Heat Pump 5 kWh % Night	3116 0.0	3130 0.0	3844 0.0	3700 0.0	2960 0.0	2708 0.8	2900 14.5	2212 9.8	3984 15.2	4168 12.5	5824 0.0	5032 0.0	43,628 4.1
Heat Pump 6 kWh % Night	3942 0.6	3424 0.3	2396 0.0	2652 0.0	2120 0.0	2284 1.9	2528 19.0	1596 8.9	2216 17.6	3152 12.2	3144 0.0	1972 0.0	31,426 4.7
Lighting & kWh Power % Night	7596 6.0	7944 5.0	7792 2.0	9888 0.0	7880 0.0	6926 0.0	7992 0.6	7716 0.3	9656 1.5	9728 4.7	9908 6.0	8188 4.8	101,214 2.6
Total Shop kWh % Night	89,410 1.0	88,790 1.0	88,870 2.0	105,830 3.0	86,100 3.0	80,650 4.0	101,130 5.0	85,940 4.0	106,130 4.6	106,830 6.3	109,810 4.9	85,920 2.6	1,135,410 3.6

Table 3 Consumptions and Percentage Night Use

	1979						1980						Annual Average
	July	August	Sept	October	Nov	Dec	Jan	Feb	March	April	May	June	
Upper Mall Temperature °C	23.3	23.7	22.0	22.5	22.8	21.7	21.5	21.7	21.4	22.2	22.1	22.2	22.3
External Temperature °C	17.0	16.7	14.3	11.0	8.4	4.3	3.7	7.2	4.9	11.0	15.5	14.5	10.7

Table 4 Internal and External Temperatures (0800 hours to 1800 hours average)

Hours Run	1979						1980						Total
	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June	
<u>HEAT PUMP 5</u>													
Compressor 1	119	209	159	123	79	75	56	50	117	148	190	174	1499
Compressor 2	116	7	34	35	23	25	28	11	33	45	124	133	614
Heating	0	0	6	22	67	75	61	44	103	41	2	0	421
Mechanical Cooling	119	209	153	89	11	1	1	0	24	108	191	172	1078
<u>HEAT PUMP 6</u>													
Compressor 1	204	208	89	62	31	47	50	11	33	83	61	1	880
Compressor 2	14	2	0	16	20	40	33	4	17	23	57	58	284
Heating	0	0	4	16	37	59	68	16	34	15	2	0	251
Mechanical Cooling	204	208	84	55	5	1	1	0	7	72	99	60	796
Free Cooling (Common)	0	0	15	55	51	35	24	76	38	51	21	11	377

Table 5 Hours of Operation

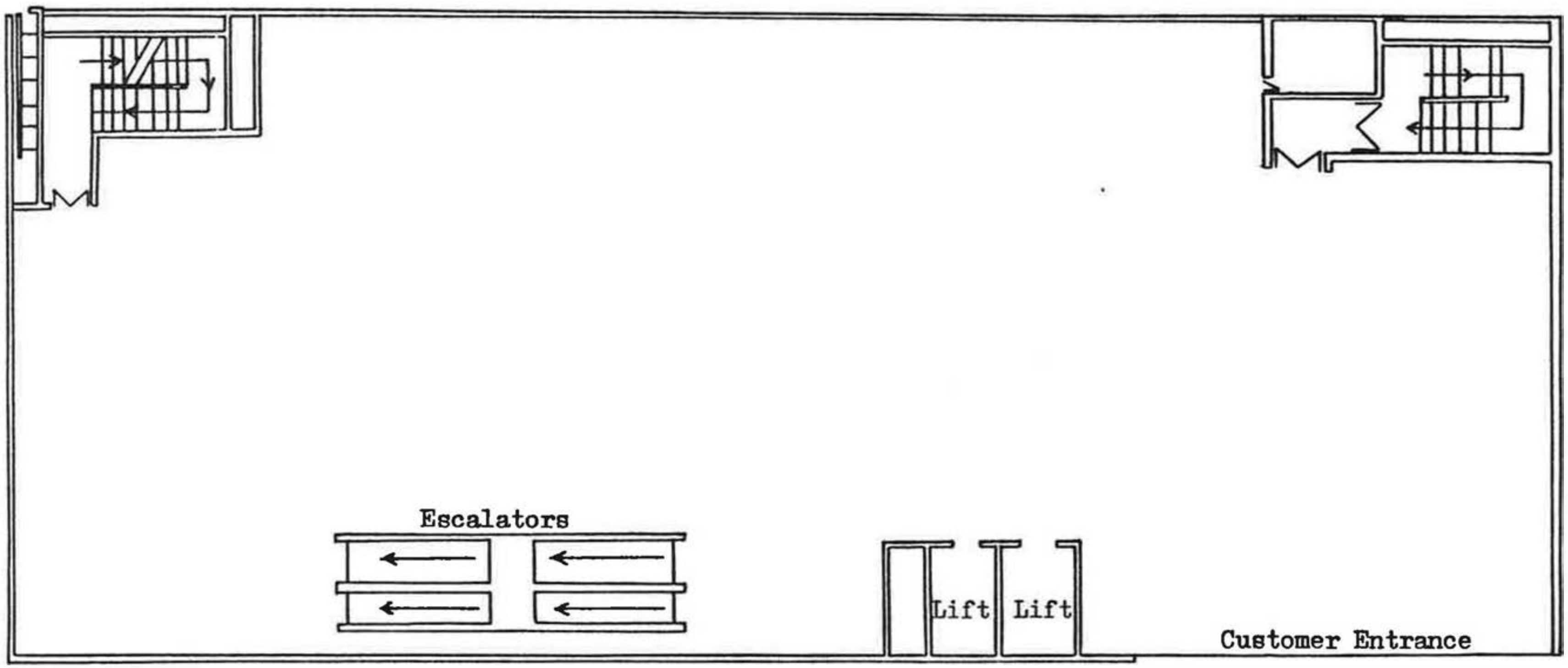


Figure 1 Upper Mall Level Floor Plan

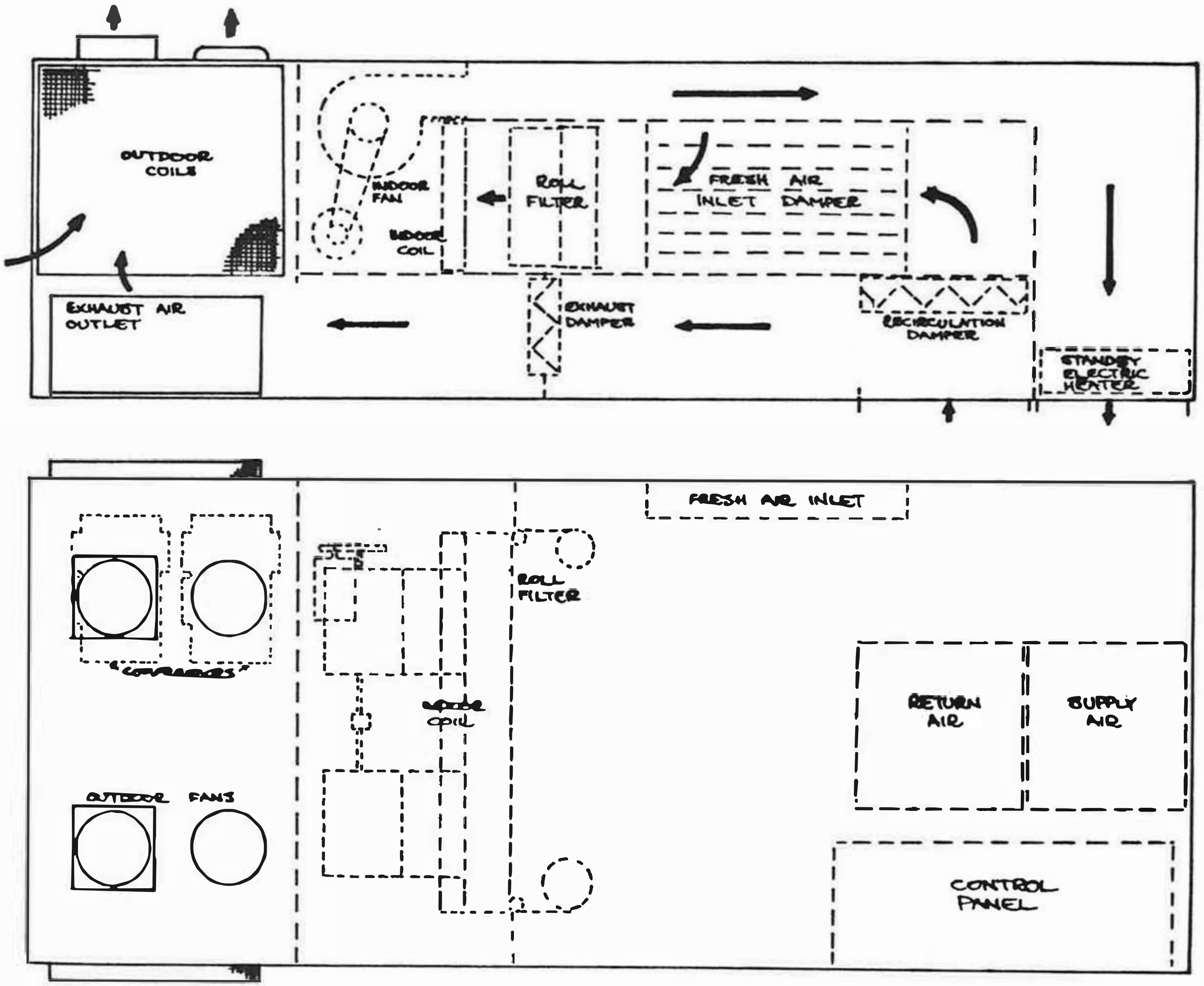


Figure [illegible] Schematic Diagram of Heat Pump

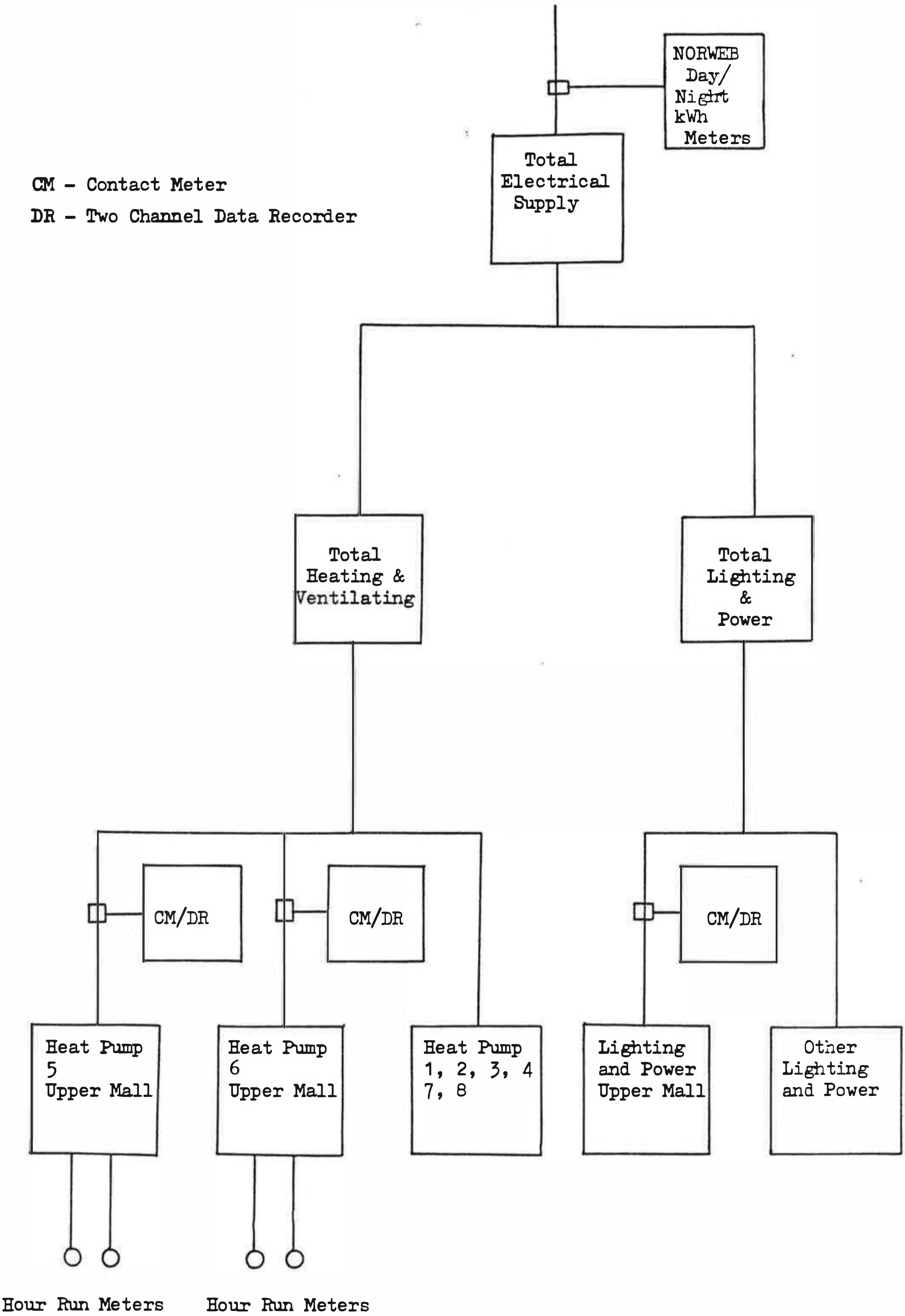


Figure 3 Electrical Metering

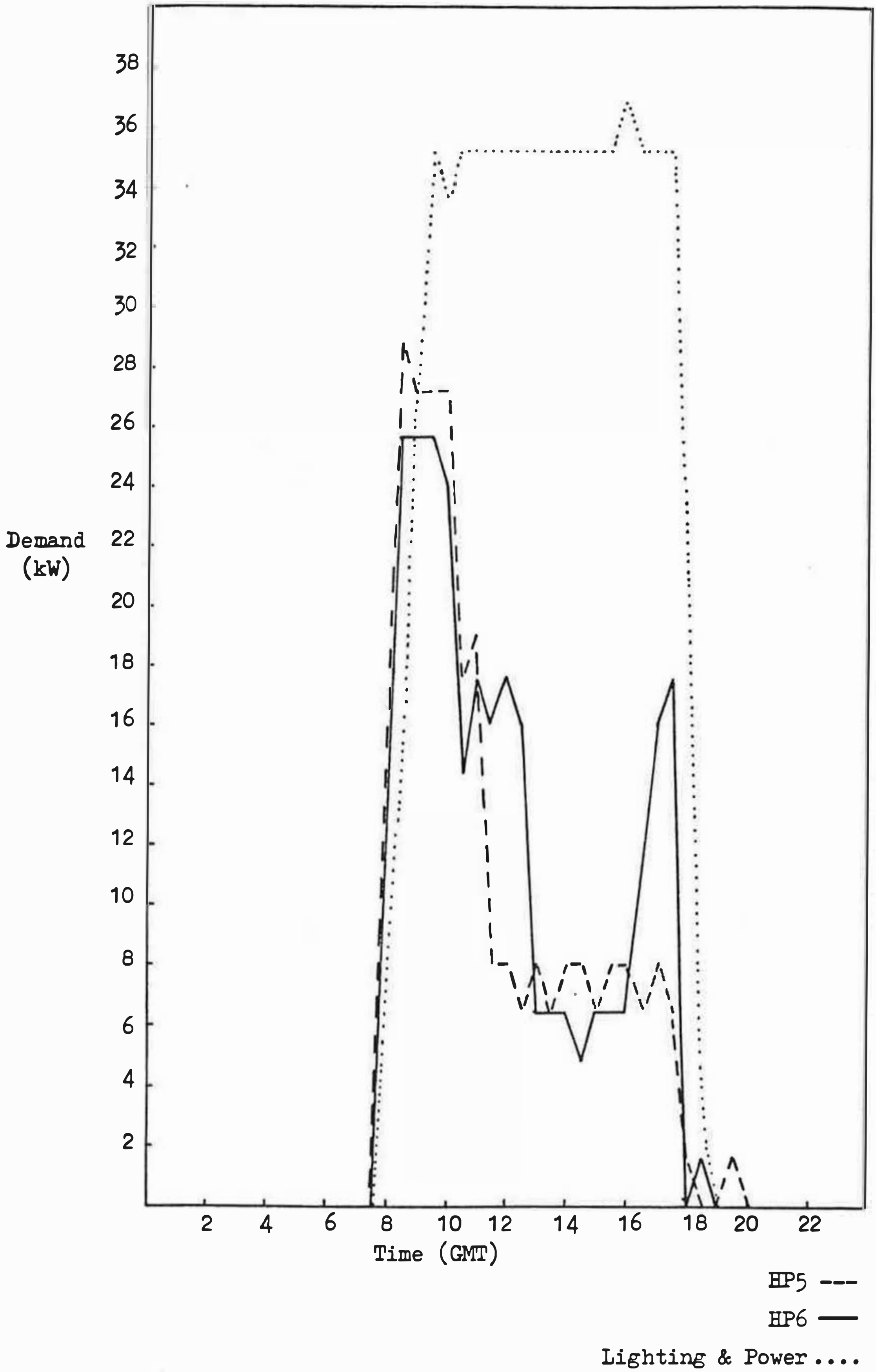


Figure 4 Demand Curve for 1 January 1980 (external temperature - 1.5°C)

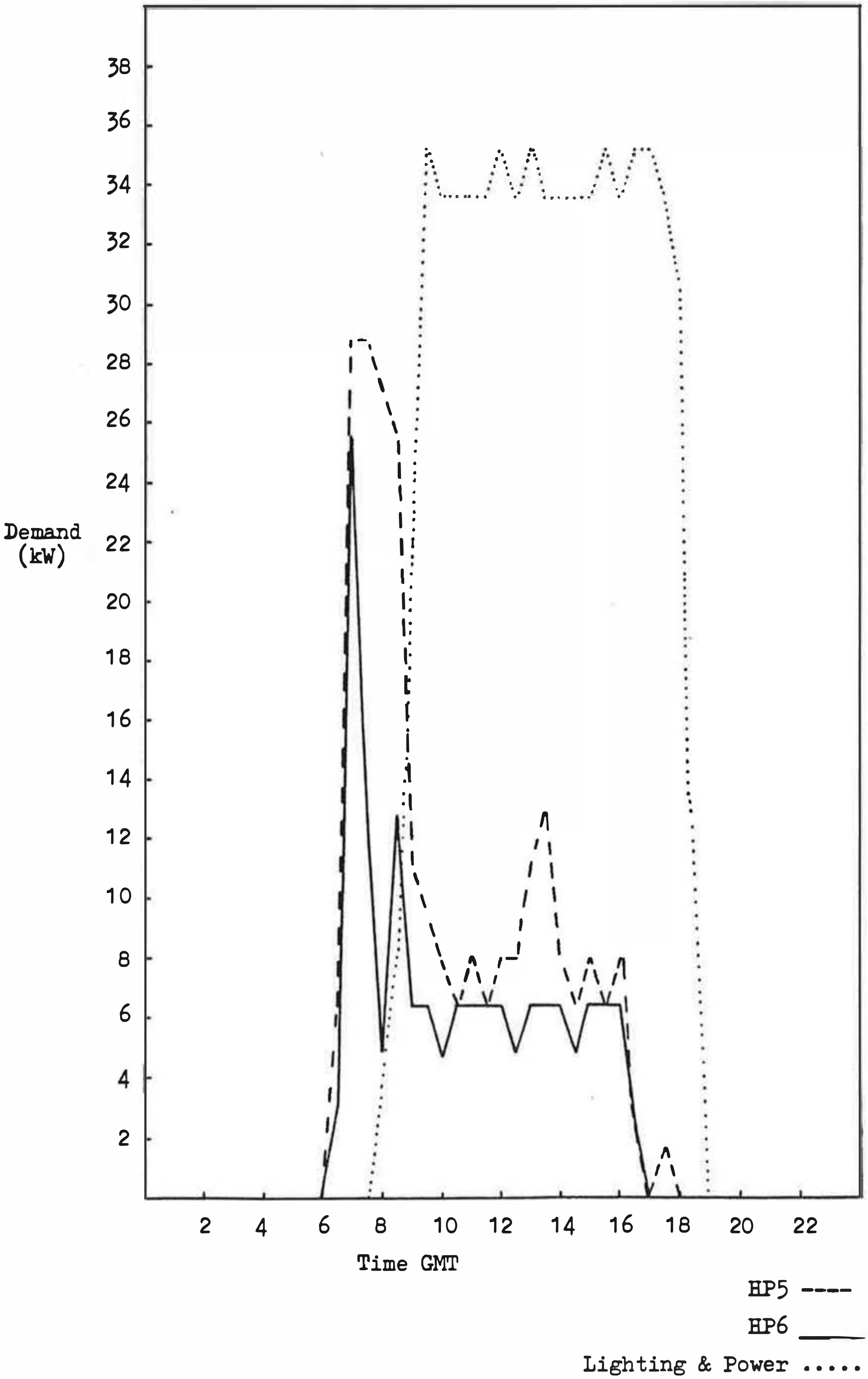


Figure 5 Demand Curve for 18 January 1980 (External temperature 0°C)

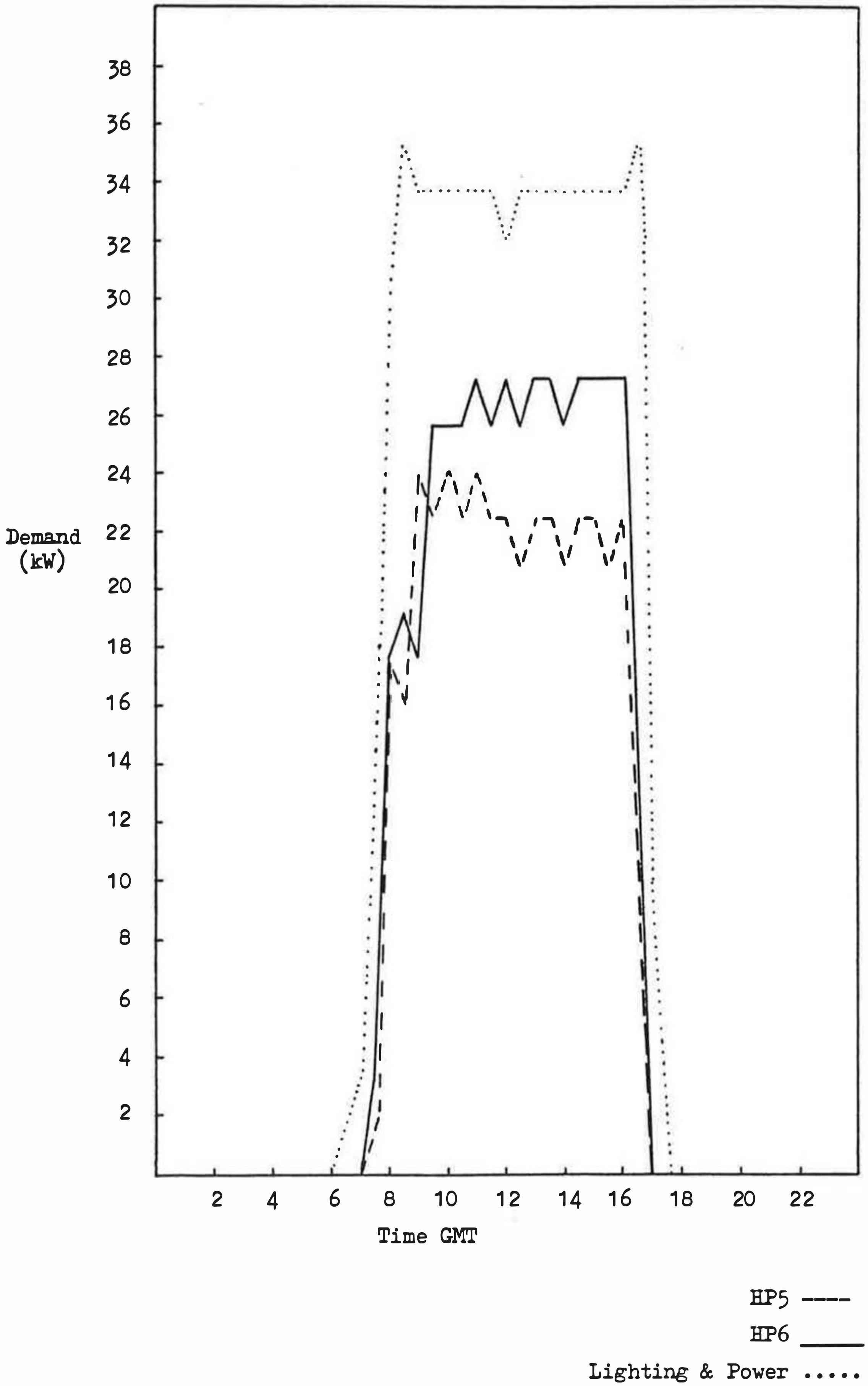


Figure 6 Demand Curve for 20 June 1979 (external temperature 21.5°C)

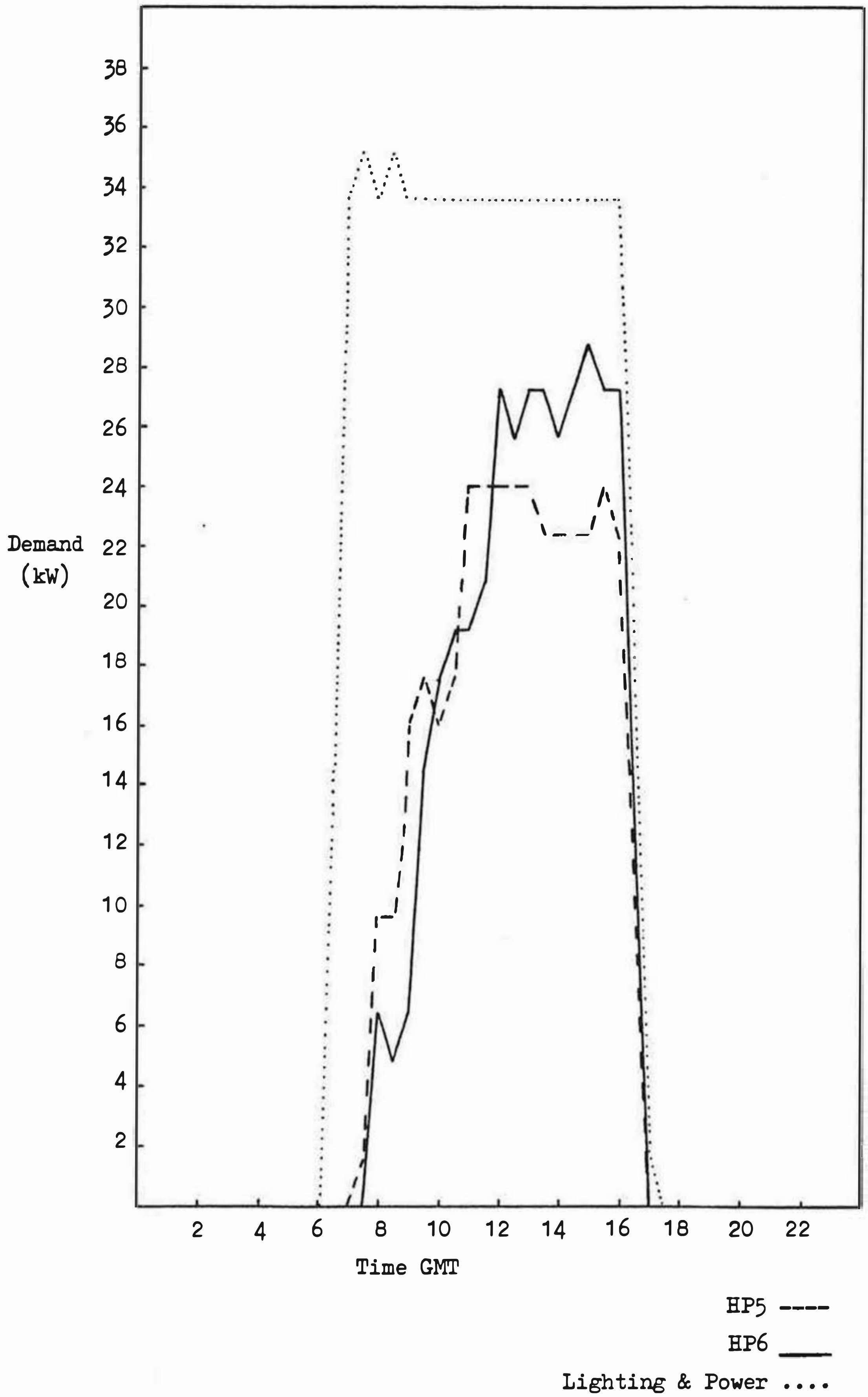


Figure 7 Demand Curve for 19 June 1979 (external temperature 22.0°C)

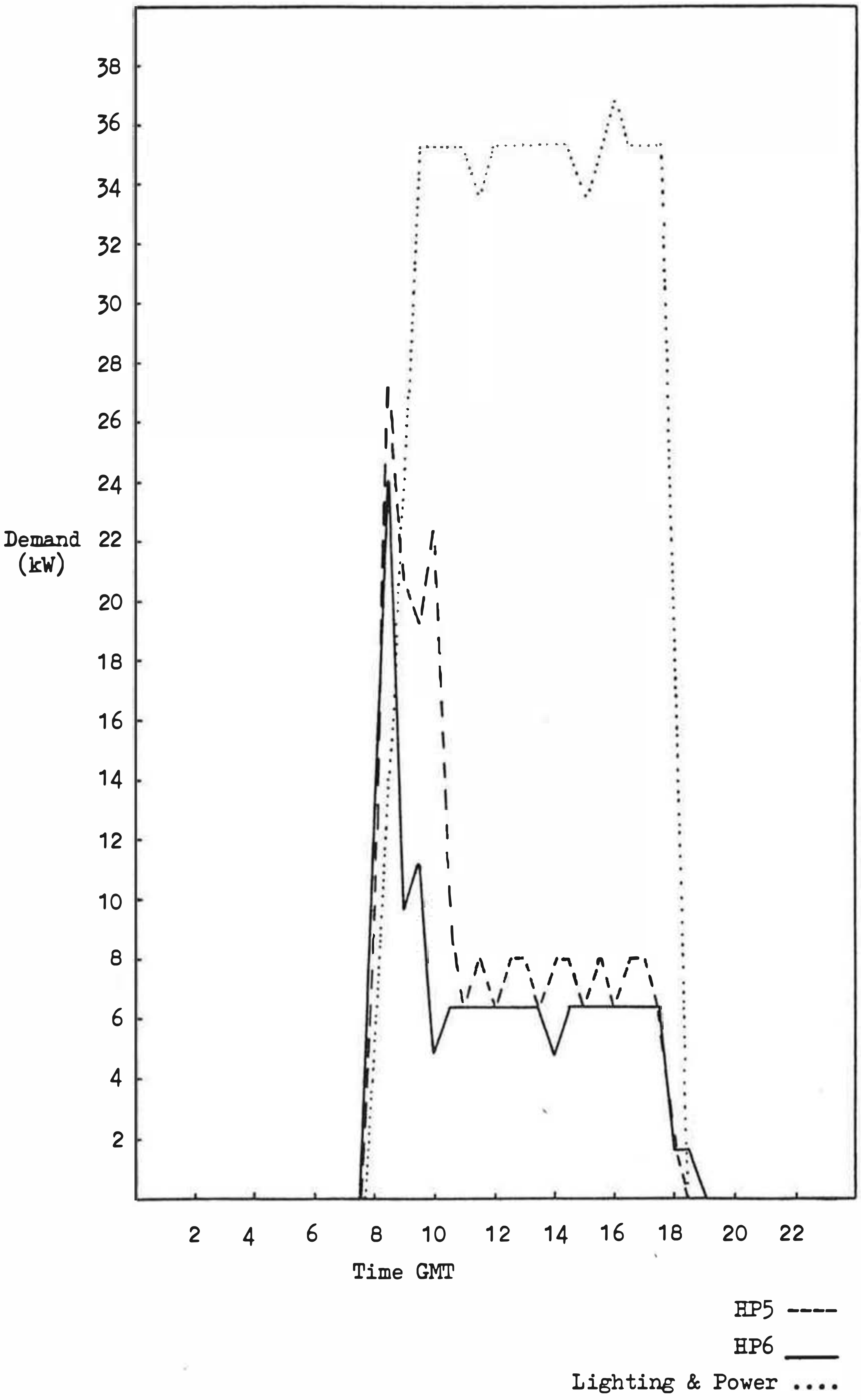


Figure 8 Demand Curve for 12 December 1979 (external temperature 7.0°C)

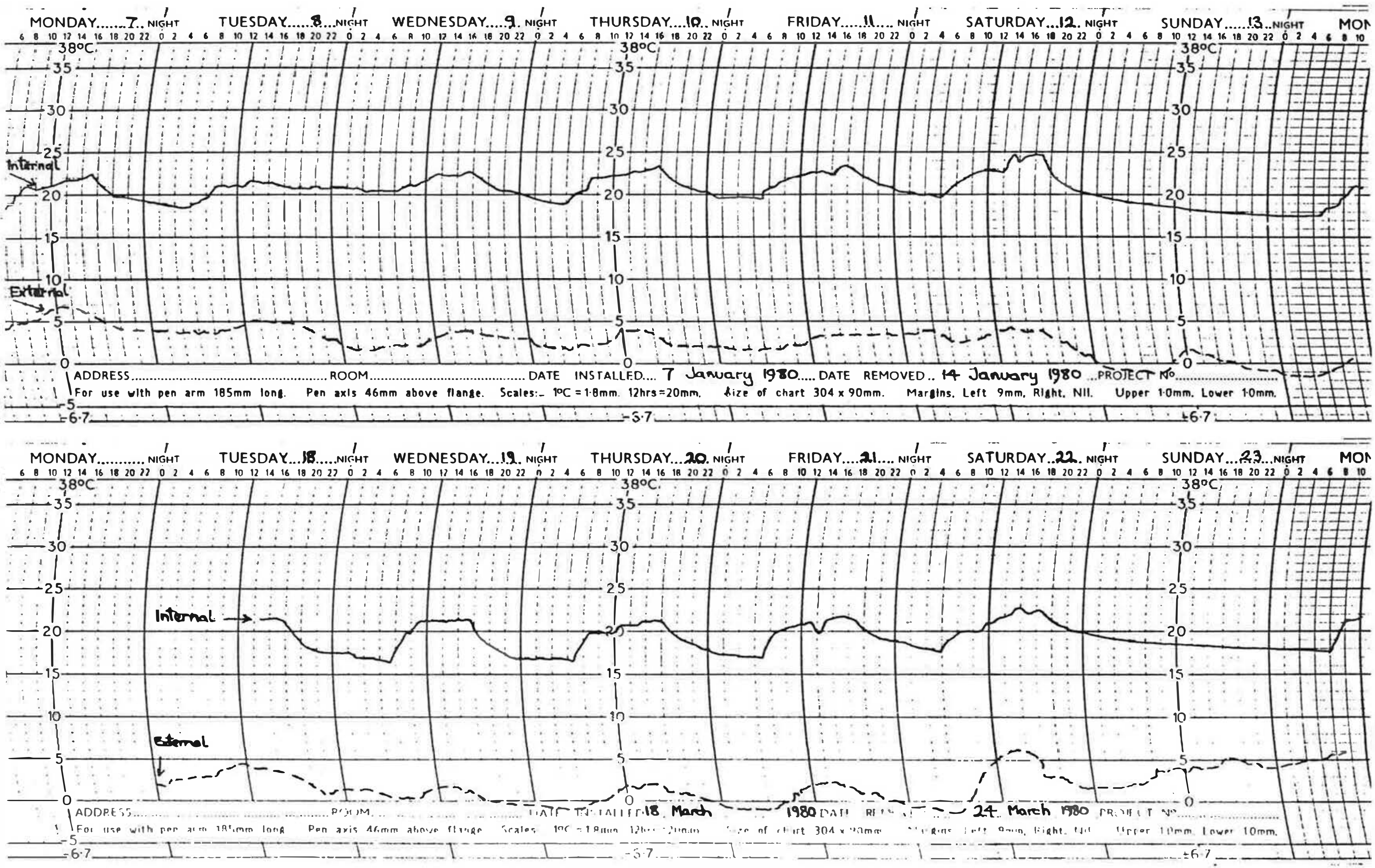
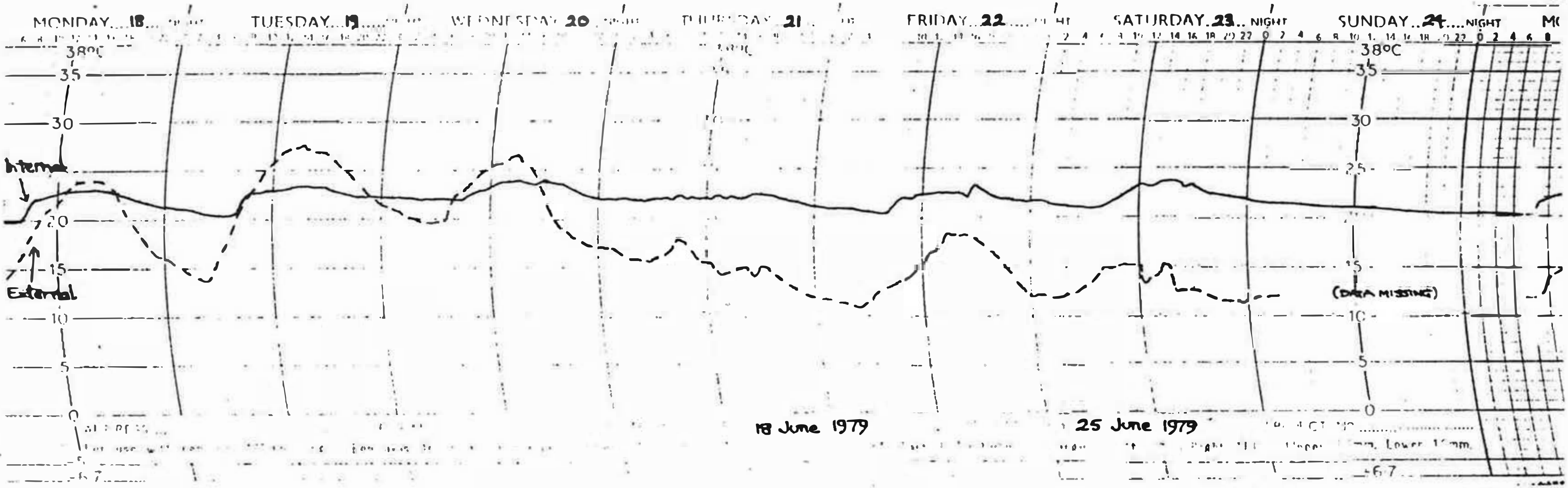


Figure 9 Thermograph Traces for Upper Mall - Winter



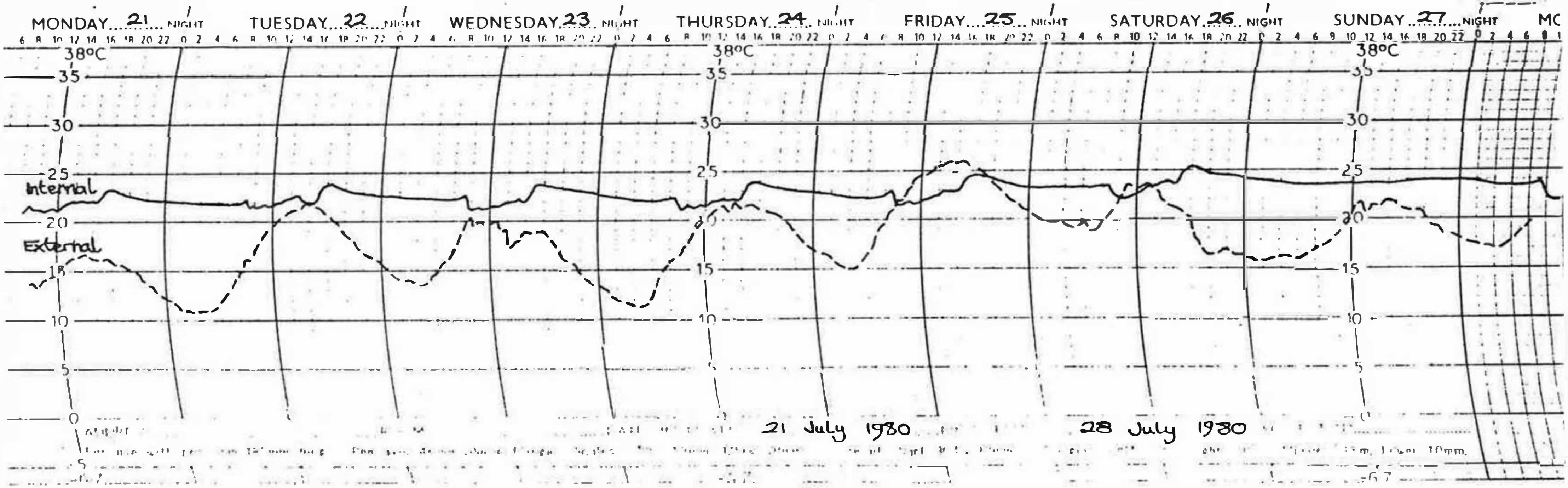


Figure 10 Thermograph Traces for Upper Mall - Summer

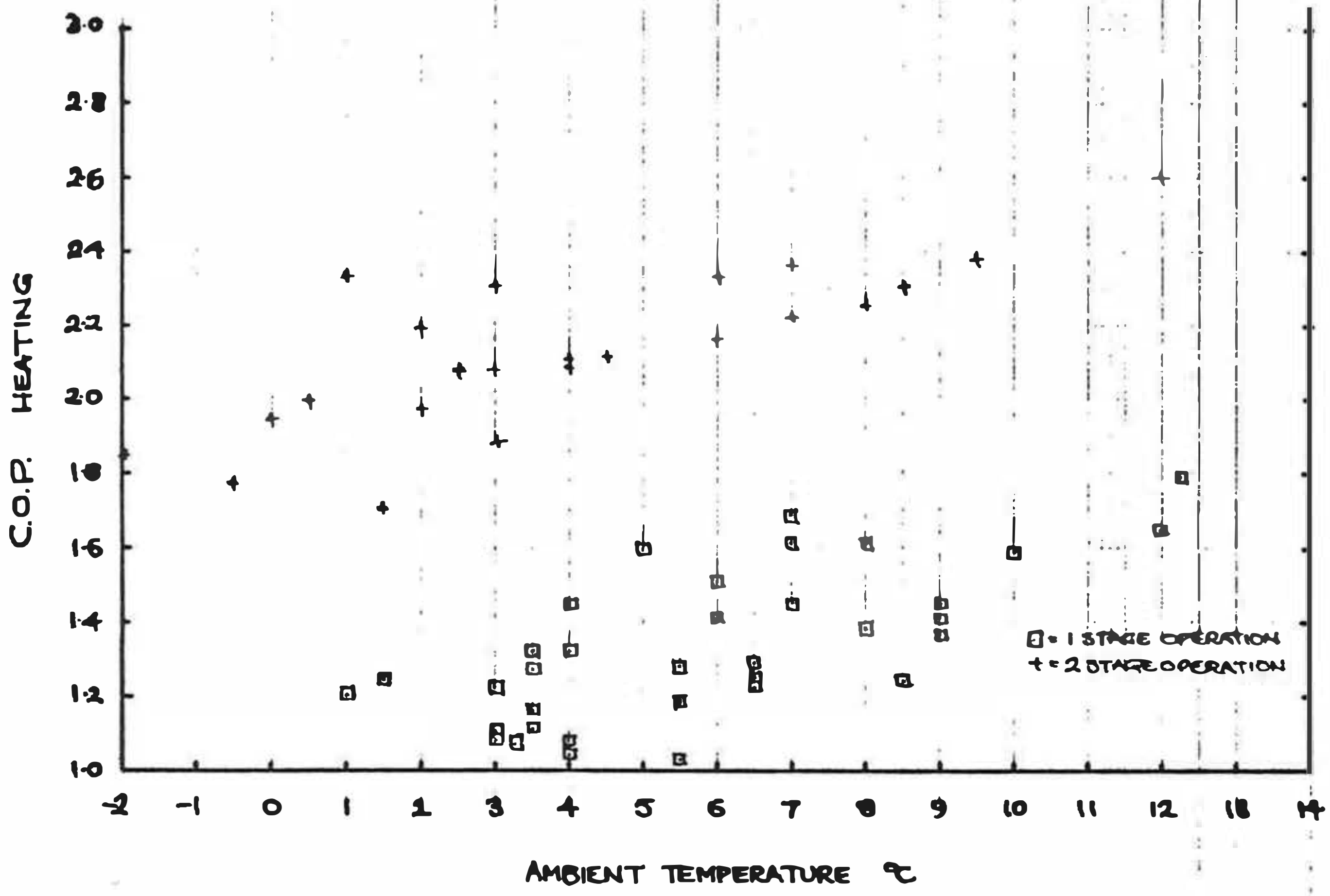


Figure 11 Heating Coefficient of Performance - Heat Pump 5 - For Compressor and Outdoor Fan, Excluding Defrosting.

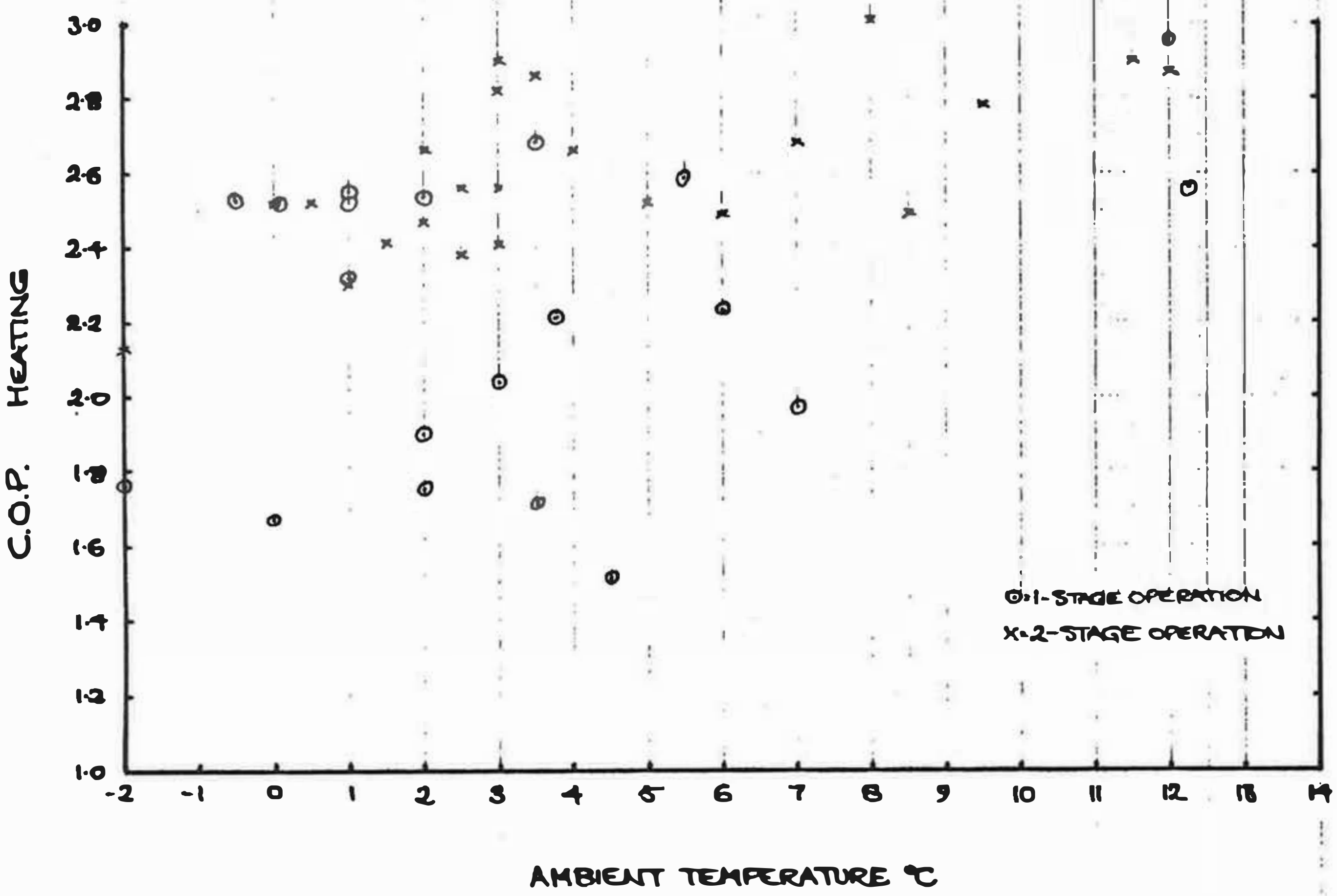


Figure 12 Heating Coefficient of Performance - Heat Pump 6 - For Compressor and Outdoor Fan, Excluding Defrosting.

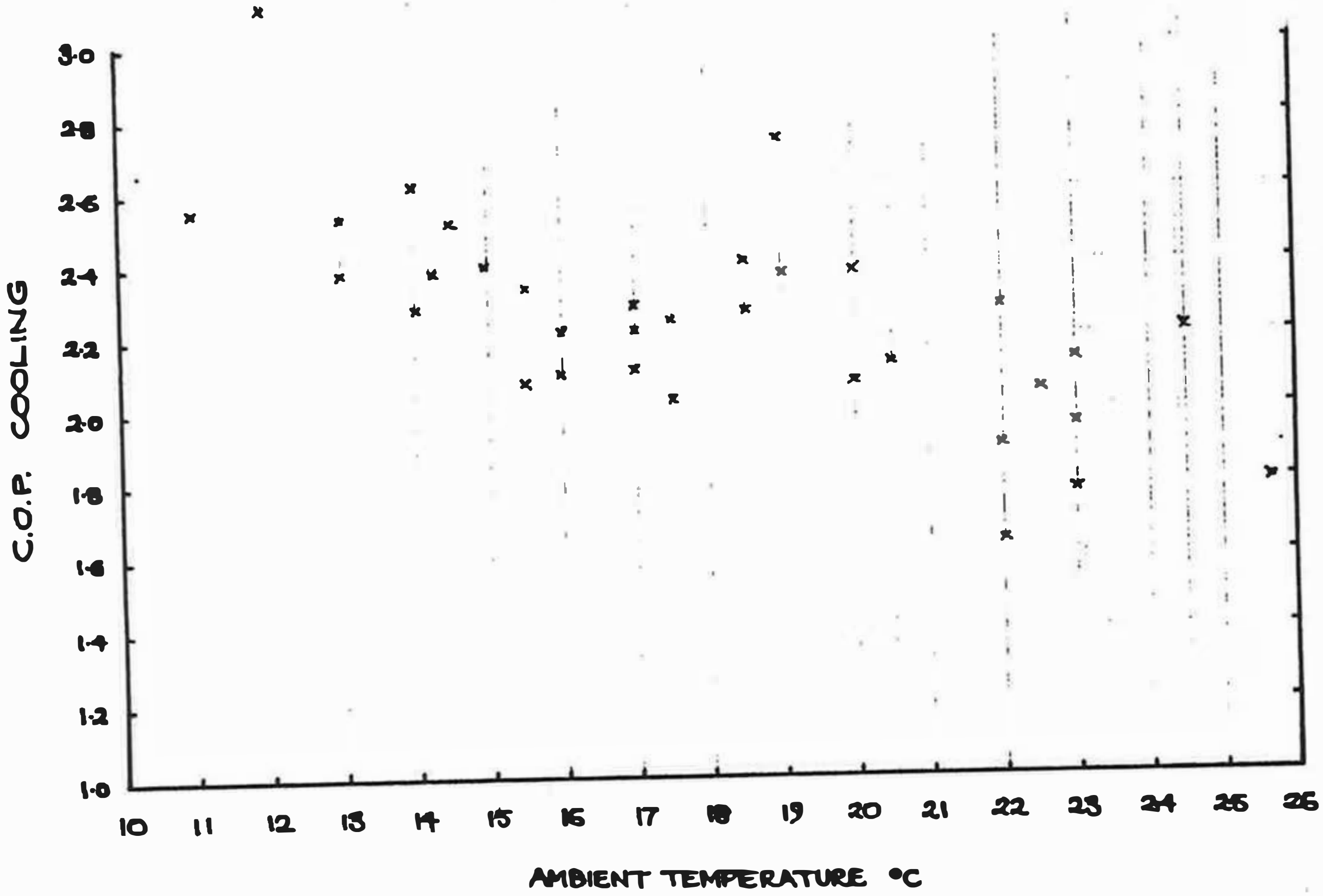


Figure 13 Cooling Coefficient of Performance - Heat Pump 6 - For Compressor and Outdoor Fan.

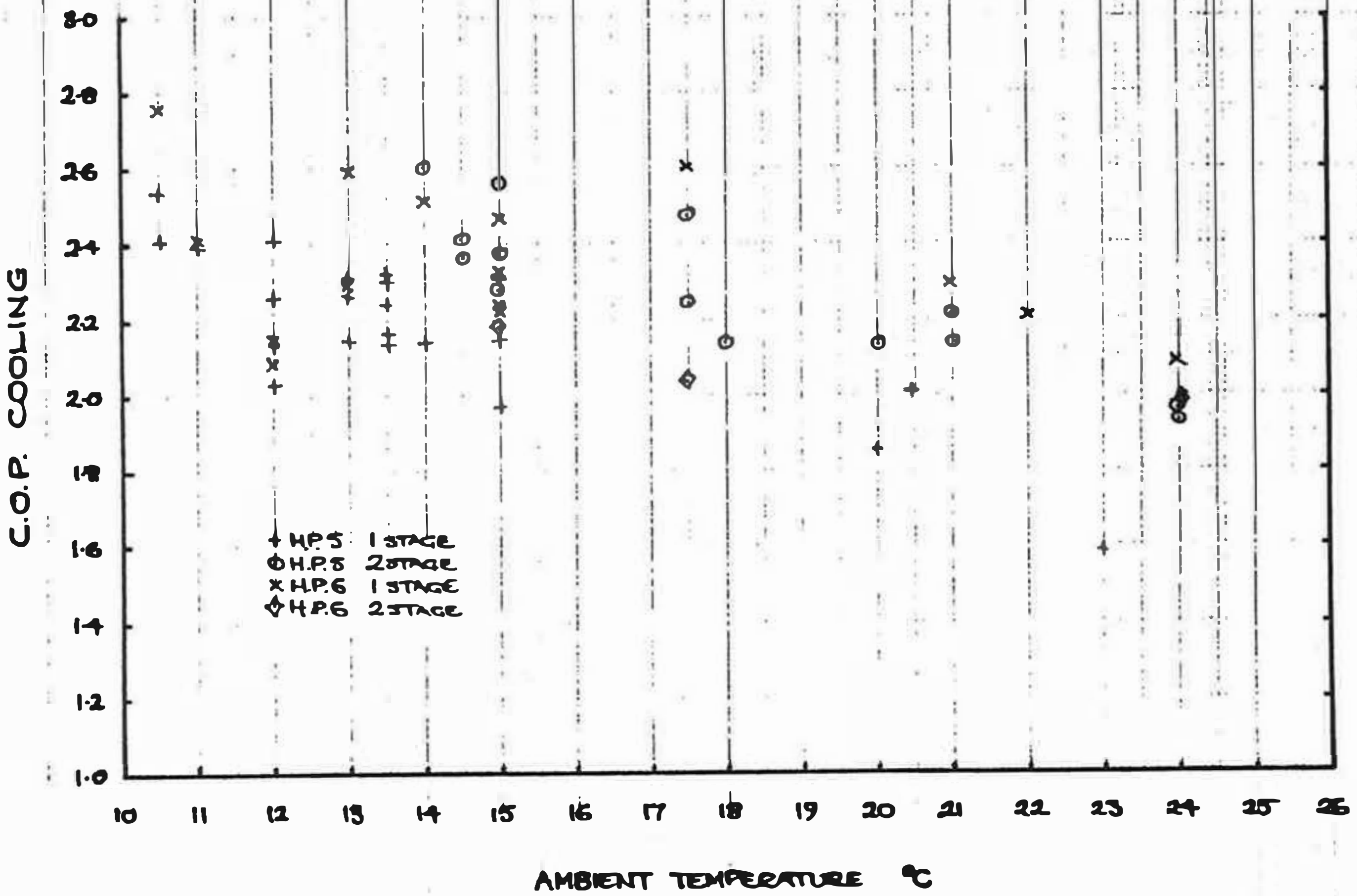


Figure 14 Cooling Coefficient of Performance - Heat Pumps 5 and 6 - For Compressor and Outdoor Fan.