probe 2

1 Aldermanbury Square

Mark Standeven, Robert Cohen and Bill Bordass report on how 1 Aldermanbury Square, the second building in our post-occupancy review series, has performed since completion.

To understand the building's detailed design readers must refer to the original article "Melting away the costs", which appeared in the April 1990 issue of *Building Services*.

The second PROBE investigation has focused on the true performance of off-peak ice storage systems. This example, 1 Aldermanbury Square, was the first speculative office building in the UK to feature the installation of an ice storage system[1].

1 Aldermanbury Square is a nine storey office building of 6 100 m^2 net lettable area (8000 m^2 gross, 7000 m^2 treated). The floor plan is roughly rectangular at 45 m by 22 m, and partly joined to a newer, neighbouring building on the south side which now overshadows all windows on that elevation.

The building was commissioned by the developers, and after a period of non-occupancy it was let to Standard Chartered Bank (SCB) in 1990 as headquarters accommodation under a full repairing lease. The Bank commissioned an initial fit-out (not by the original m&e consultant) to tailor the building to its needs, reducing usable area to 5774 m^2. Maximum occupancy rose to about 250 occupants, but currently it is down to 217 giving a density of 27 m^2/person.

core services

The building's services were sized for an equipment load of 30 W/m^2 and a supply air temperature of 9°C, with an option to cater for a maximum of 60 W/m^2 at lower supply temperatures. As with many 1980s speculative developments, the loads have proved to be less than 40% of the lower design value, the installed office equipment load being 7 W/m^2 and the lighting load 12 W/m^2 (spot measurements confirmed 350–500 lux on the working plane).

The building is ventilated and cooled by a Carrier fan-powered Variable Air Volume and Temperature (VVT) system. Chilled water is provided by two Carrier reciprocating chillers with four stage compressors, installed in series with eight Calmac ice storage tanks in the basement plantroom. Each chiller has a cooling duty of 340 kW by day and 240 kW by night.

Each ice tank has 6340 litres of water and 560 litres of glycol coolant in the coiled mat of the plastic heat exchanger. The tanks have 50 mm of expanded polystyrene insulation around and beneath them, as well as an aluminium casing. The chilled water has a 30% (by weight) ethylene glycol solution to allow the system to operate below 0°C and build ice.

The building is not fitted with a central bems. Instead, the Carrier Assured Comfort System (ACS) monitors and controls the VVT system. If a minimum of eight mixing boxes (determined through experience) request local cooling, the ACS signals the Staefa control panel to reduce the primary air supply temperature. If free cooling is not available, the cws pumps then circulate chilled water through the three main office ahu coils, supplying air to all mixing boxes. For the mixing boxes not calling for cooling, primary air dampers move to minimum fresh air, increasing the recirculation of plenum air.

If heating is required—but recirculation of the hot void air cannot maintain conditions — the mixing box heating coils will then come on. It is therefore possible for central cooling and local reheating to occur simultaneously.

building fit-out

The lower ground floor was replanned to incorporate a kitchen and staff restaurant, meeting rooms, a communications room, an IT room and several small offices and stores. The third and fourth floors were replanned to provide executive offices and meeting rooms. A white noise system was installed in all the open-plan office areas to improve conversational privacy.

Modifications were made to the ceiling voids, allowing individual temperature and condition control in executive offices. A kitchen was also added to the fourth floor to serve executive dining and conference rooms. Additional air supply terminals with fan-powered mixing boxes were provided for the dining areas on the lower ground and fourth floors.

In 1993 modifications were made to the controls to reduce running costs and improve plant operation. Originally, under frost protection mode all plant was activated. By using an additional relay only the boilers, gas boosters and 1thw pumps would be enabled. A

separate relay activates all the ahu supply and extract fans during hours of occupancy.
The Staefa controller was revised to allow free cooling when there is a cooling demand from the Carrier ACS management system. Currently, the free cooling set-point for primary air is 10°C, only 1°C higher than the original intended chiller supply air temperature. This keeps all cooling plant and associated pumps switched off until the external ambient rises above 10°C, while a 30 minute delay timer reduces plant cycling around that set-point.
In 1995 the Carrier software was reconfigured to enable the mixing boxes to be reset automatically to default parameters at the end of each day.
Night setback points have been given maximum spread (–7°C to 41°C) to prevent mixing boxes demanding plant start-up during exceptional weather. The control now relies on ahu frost thermostats to bring on the central plant while holding off the mixing boxes.
Main office lighting is by high frequency fluorescent downlighters. Lighting around the core is from double-tube PL lamps in 200mm^2 luminaires. The estimated load of 12 W/m^2 is well under the 20-25 W/m^2 of a typical 1980s prestige office building.
The low installed load and reasonable control means that annual energy consumption for lighting, estimated at 50 kWh/m^2, is low compared to typical practice of 82 kWh/m^2.
On the second floor there are 56 pcs, four laptops, 14 laser printers and seven fax machines serving 62 staff over a usable area of 944 m. Average installed load is around 7 W/m^2.
These figures represent an upper limit as the two executive floors have much lower staff densities at 51 and 40 m^2/person. At 20 kWh/m^2, estimated small power energy consumption for the whole building is lower than the *Energy Consumption Guide 19* norm of 29 kWh/m^2.

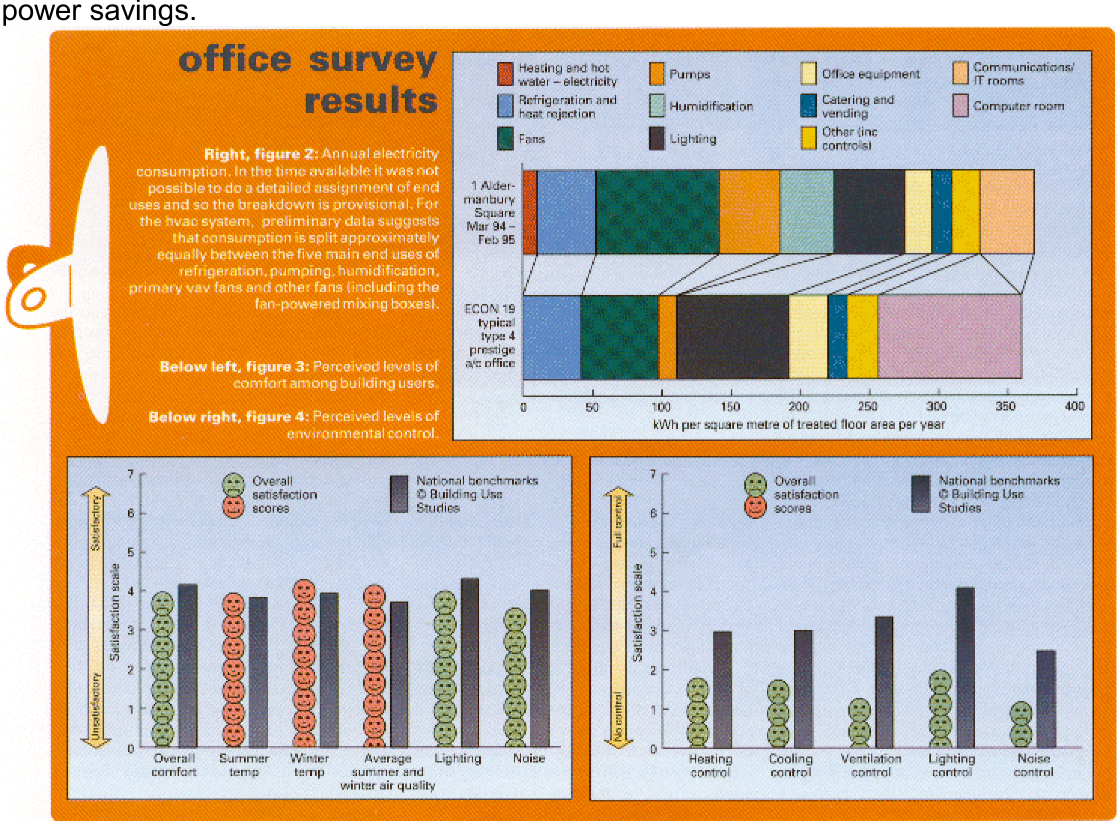
ice storage

All eight Calmac ice tanks have a sensible capacity of 100 kWh, a latent capacity of 570 kWh and a maximum cooling capacity of 5360 kWh. The ice tanks form an indirect system, as the fluid which is frozen does not circulate directly to the load. Instead, the chillers and ice store are used in series with the two chillers downstream of the ice tanks. This arrangement is also referred to as 'store-led' and during discharge the chiller will operate at lower temperatures and hence lower co-efficient of performance (cop).
The operating and maintenance manuals state that after seven hours charging there is a total of 3521 kWh cooling capacity. At night the chillers have a 240kW cooling capacity providing chilled glycol and water for ice building at a temperature of –6·4°C. In seven hours the chillers can create a maximum of 3360 kWh of cooling capacity.
However, the rate at which the water in the tanks will freeze is a function of the coil performance, the flow rate and the temperature of the glycol coolant. Furthermore, the rate of heat transfer will fall during the charge period as ice builds up around the coil.
Based on eight tanks in use, a chiller flow rate of 213 litres/s and the manufacturer's sizing method, it seems that heat transfer through the coil would enable 75%of the installed capacity to be charged in a seven hour period (ie 4020 kWh of 'coolth'). Since this is 20% greater than the output from the chillers, it is clear that the charge rate is limited by the chiller output and not by the heat exchange capacity of the coil.
For a 10-h day with full ice storage and two chillers operating at 340 kW, the maximum average cooling output is 1016 kW. Over the treated area of 7011 m^2 this is equivalent

to approximately 145 W/m^2.

Overall, there is significant over capacity in the installed cooling system. However, the system is not (or maybe cannot be) managed to maximise the load shifting and load levelling capabilities of ice storage. Load shifting would be enhanced if the night mode output of the chiller were able to fully charge the storage capacity, while load levelling could be achieved if the daytime operation of one or both of the chillers were regulated to minimise the monthly maximum demand of the building.

Ice storage in the cooling system offers three potential advantages — running costs can be reduced by operating chillers at night on off-peak rate electricity to make ice, capital savings will accrue as the chiller can be smaller than demanded by the peak load and lower supply air temperatures associated with ice storage can lead to ductwork and fan power savings.



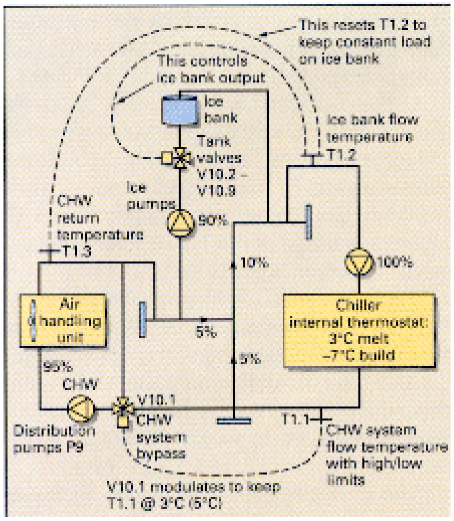
Right, figure 2: Annual electricity consumption. In the time available it was not possible to do a detailed assignment of end uses and so the breakdown is provisional. For the hvac system, preliminary data suggests that consumption is split approximately equally between the five main end uses of refrigeration, pumping, humidification, primary vav fans and other fans (including the fan-powered mixing boxes).

Below left, figure 3: Perceived levels of comfort among building users.

Below right, figure 4: Perceived levels of environmental control.

Before entering into a performance analysis, here is a quick résumé of how the system works. The chillers and pumps are started by a time clock at midnight GMT (to coincide with the start of off-peak rates) and the chiller's internal thermostat is set to –7°C. Ice build finishes either at the end of the night rate electricity period (07.00 h GMT) or when the ice inventory meter in one of the tanks indicates 100% ice. To prevent damage to the ice tanks and coils it is important that the chillers are shut down at 100% ice, leaving a column of water in the centre of the coils and an expansion layer of water on top of them.

Control is best handled on the ice bank return temperature which can be set on commissioning, but the internal chiller thermostat will offer a second line of control and the ice level indicator a third. During ice build, the chilled water distribution pumps are shut down to prevent circulation through the secondary circuit to the three ahu cooling coils.



The chillers are enabled by a time clock signal at 07.00 h, which resets the internal thermostats from –7°C to 3°C (figure 1). At the start of SCB's occupancy, sensor T1.1 was set to demand chiller operation of cws flow temperatures greater than 3°C. In the first year of operation it was found that 5°C chilled water flow was sufficient to meet demand, and this is now the permanent daytime setting of sensor T1.1.

The original designers also specified that if cws return temperature from the load is between 8°Cand 12°C the tank valves (V10.2 to V10.9) should open to enable chilled water to circulate through the ice banks and maintain the ice bank flow temperature at 6·2°C. The tank valves were controlled according to the ice bank flow temperature to adjust the temperature difference across the ice bank and maintain a constant load on the bank. The chillers would then operate to reduce the cws flow temperature to 3°C.

In practice the plant is not operated like this. The building occupier found that the 3°C flow temperature was unnecessary and raised it to 5°C. Despite this, high proportions of ice were still left at the end of days when the chillers had been in operation. The response was to hold off the chillers until the chilled water return temperature (T1.3) reaches 6·4°C. Generally the ice level meter indicates 15% when this happens.

As the ice tanks are not isolated when the chillers are enabled, warmed return water continues to run through them and the ice sometimes fully melts, making it impossible to completely recharge them during the off-peak period.

In principle, the common header could be used to bypass the tanks when the ice has been depleted, and also to bypass chiller evaporators while the chillers are held off, thus removing a significant pressure drop (figure 1). This potential flexibility inherent in the hydraulic arrangement is not being fully exploited, and would probably require motorised valves and enhanced controls.

The most serious problem has been a pinhole leak in the coil of one ice tank, which has been out of action for 18 months. Due to the nature of the installation it is impossible to remove the coil without disturbing the cws primary pipework, removing cable trays installed during fit-out and tipping the tank over. The latest idea is to cut each coil from the supply and return headers until the leaking coil is reached, replace it and rebuild the coil using sleeves to rejoin the cut coils.

A burst coil has also been identified by a mixture of water and glycol overflowing from one of the storage tanks. This has been isolated and so six tanks are currently operational.

Several other problems have been experienced. Thermosyphoning of chilled water through the ice tanks to the cooling coils between plant shutdown and ice-charging has meant that ice tank water had to be frozen from near ambient temperatures. This was solved by three-port valves (V10.2 and V10.9 on figure 1) to the ice tanks which now close on plant shut down — usually at 18.00 h — and isolate the tanks from the primary circuit.

The premises department lacks confidence in the ice inventory meter, which works on the basis that ice has a greater volume than water and so measures the fluctuation in water level to determine the proportion of ice in the tank. Unfortunately, only one of the eight tanks is metered which means that any water loss or atypical behaviour of that tank will affect the control of all tanks.

A 10 minute delay was introduced in 1993 so that an overcooling alarm by the chilled water flow temperature sensor did not go off every morning when the chilled controls sensed overcooled water at –6°C. This delay allows the secondary cws pumps to mix the chilled water (which has been used to build ice at –7°C) with the glycol which has stood static overnight in the distribution circuit. Previously the chillers regularly locked out on low temperatures.

Summertime metering of night rates (00.00 h to 07.00 h GMT or 01.00 h to 08.00 h BST) are not synchronised with the timing of occupancy which is from 07.00 h BST. Therefore, there is only six hours off-peak ice building prior to occupancy. To counter this in warm conditions like the summer of 1995, SCB timed the ice build to start at midnight BST, therefore incurring one hour of peak rate charges.

This practice should be avoided and the chillers run for longer in the daytime, as the plant operates less efficiently in charge mode and there are no summertime maximum demand penalties. Alternatively the building operators could negotiate alternative off-peak periods.

On many occasions after the ice store was fully depleted, SCB has not been able to make 100% ice during the seven hour charge period for the following day. The Bank has identified faults on plant, such as condenser water pumps, the cooling tower, ice tank circulation pumps and the chillers which have caused failure to build ice on average at least once a fortnight.

energy issues

The use of ice storage incurs efficiency penalties. The chiller cop and hence cooling output drops significantly due to the lower evaporator temperatures required to make ice. An additional pump set is needed to distribute chilled water through the ice, and the use of glycol and water as coolant reduces heat transfer performance. Standing losses from the ice tanks further reduce efficiency.

To partially counter such system losses, lower night-time air temperatures can be exploited to either reduce the condenser temperature or indirectly improve condenser cooling efficiency. At 1 Aldermanbury Square the chiller condensers operate at constant temperature, but the cooling tower can have improved night-time performance.

Table 1: Chiller cooling costs for a possible 100 kW contract tariff

Tariff	Mode	Power absorption (kW)	Cooling capacity (kW)	Coefficient of performance	Electricity charge (p/kWh)	Chiller electricity cost (£/h)	Chiller cooling charge (p/kWh$_{cool}$)
Off-peak	Day	116	340	293	512	594	1.75
Night	116	242	210	2.19	2.54	1.05	
Contrac	Day	116	340	2.93	425	493	145

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	Night	116	242	210	4.25	4.93	2.04

Table 2: Electricity costs for the building under different operating modes

Mode	Current arrangement Off-peak tariff Ice storage	Effect of switching tariff Contract tariff Ice storage	Effect of switching tariff and not using ice storage Conventional
Day mode consumption (MWh)	1884	2606	2476
Night mode consumption (MWh)	722	0	0
Total electricity cost (£)*	170 217	168 443	161 935

*Includes current fixed costs of £32 583 covering maximum demand, availability and standing charges and vat @ 17.5%

Table 1 shows the operating costs of the two chillers. It is estimated that some 70% of chiller operating hours are in night mode, and 30% in day mode. Due to poorer chiller performance at night this results in a 20% greater electricity consumption by the chillers than would be the case with no ice storage. This is based on chiller performance only and ignores the standing losses from ice and the use of glycol coolant.

It is likely that resultant power station CO_2 emissions per kWh are at least 16% higher than would be the case with no ice storage, even though power station CO_2 emissions per kWh on a summer night are perhaps some 20% lower than daytime emissions. The system relies on lower off-peak electricity charges to more than compensate for this reduced energy efficiency.

Table 1 also shows the chiller cooling costs for a possible 100 kW contract tariff. The flat rate tariff (typically 4·25 p/kWh) offers no benefit for off-peak use, and the cost per unit of cooling would be less during the day due to the higher chiller efficiency when operating in day mode.

In monetary terms there appears to be a significant benefit in operating the chillers on an off-peak tariff. However, the overall benefit of ice storage is also sensitive to the proportion of the total electricity consumption which is used at off-peak rates. In the 12 month period spanning February 1994 to March 1995, 28% (722 MWh) of the total electricity use by the whole building was consumed during the off-peak period and 72% (1884 MWh) during the day.

This means that 1 Aldermanbury Square is just under the economic breakeven point for the off-peak tariff. Only if the proportion of total electricity consumption in night mode were above 30% would it be cheaper to use the off-peak tariff.

Total electricity costs for the building under three scenarios are shown in table 2. The results confirm that the energy cost savings made by running the chillers at night using cheap rates have been offset by the larger daytime building consumption which incurs a higherdaytime unit rate (5.12 p/kWh) than if the building were on a flat rate 100 kW tariff (at 4.25 p/kWh).

If the system were simply switched to a flat rate of 4.25 p/kWh ,then based on the way the system is currently run almost £2000 would be saved. If a conventional system without ice storage were used, assuming a 5% saving on the total electricity

consumption, it is estimated that over £8000 could be saved. It is believed that the system installed at 1 Aldermanbury Square could be operated in this way.
If the chillers were metered separately from other electricity usage and it were possible to negotiate the best tariff for each meter, the best of both worlds would be possible and maximum cost savings might be achievable.
These straightforward sums show that the economic case for ice storage must not be made in isolation to the overall electrical consumption of the building.
Since this installation was completed there have been developments in the approach to ice storage in both equipment and operation. Calmac tanks now have a thermal barrier above the coils as a fail-safe measure to prevent complete freezing. Operational strategies have also moved away from simplistic chiller priority-ice peak lopping to methods of meeting a more variable UK load profile.
Figure 2 reveals how 1 Aldermanbury Square compared to the *Energy Consumption Guide 19* benchmarks[2] for an air conditioned open-plan office building, after taking account of the atypical restaurant, IT and pabx power consumption. Annual gas consumption is good at a figure of 32 kWh/m^2, while annual electricity consumption is worse than typical at 371 kWh/m^2. Total CO_2 emissions at 282 kg/m^2/y are better than the typical value[2] of 307 kg/m^2/y.

the staff survey

The self-completion questionnaire developed by Building Use Studies for the PROBE study was used, with additional customised questions to assess features such as the ceiling outlets and the white noise system. Out of 119 questionnaires distributed only 61 were completed, a somewhat disappointing response.
66% of respondents said they were professional or managerial, the remainder being clerical. Almost everyone worked a five day week, spending 8–10 h in the building. Over 90% said they spent more than six hours at their desks.
Of those surveyed, 58% were men, 81% were over 30 and 42% said they sat near a window. 75% of respondents had worked in the building for over a year. The most common size of work group was five. The use of pcs is quite high with an average usage of 4·6 h/day. 20% reported more than seven hours of computer use.
Compared with Building Use Studies benchmarks, 1 Aldermanbury Square is in the lower 30% of UK office buildings for overall comfort (figure 3). Winter and summer temperatures are better than national norms, but lighting quality is perceived as being poor and the noise levels as very poor.
The air quality in summer and winter is perceived as being stuffier than the norms, but slightly less smelly. The air is also perceived to be significantly more humid (the original design stipulated 40% rh at 23°C, and 50% rh at 21°C).
There were many complaints about the noise of other people's conversations (mainly on the telephone) and from meetings in open-plan areas, and a few complaints of external noise. 52% of people were dissatisfied with the white noise system, 31% neutral and 17% satisfied. Several occupants did not even realise there was a system. 76% thought the level of conversational privacy was unsatisfactory and only 12% were satisfied with personal privacy.
A separate occupant survey carried out by UMIST corroborated that noise, privacy and local control are perceived as significant negative attributes.
On lighting, the evidence from the Building Use Studies survey was contradictory. Respondents generally thought the levels of natural light were too high, but glare from

sun and sky was low. Perceived levels of control for heating, cooling, ventilation and noise were much lower than the benchmarks, which is slightly surprising considering the VVT system and the number of local controllers on each floor (figure 4).

Some 57% of staff had requested changes to the heating, lighting, ventilation or air conditioning. Just over half of this group felt that the response was satisfactory and 30% thought the change was effective. On average, staff reported that the building causes a perceived 4·2% productivity loss. Staff who are satisfied with overall comfort differ significantly in their perceptions of productivity from those dissatisfied.

Thermally satisfied staff perceived that they experience a productivity gain of 2·8%, with dissatisfied staff reporting a loss of 7·9%. Unusually, sitting next to a window in this building has a negative effect on productivity perceptions. Perceived control of heating and ventilation are associated with perceived productivity.

The building is more complicated than others of its kind, reflected by the use of permanent in-house maintenance staff. The ice storage system suffers problems and, frustratingly, still fails to produce ice about once every two weeks.

The Carrier VVT system is liked by the operators because of the nominal control it provides. (The management was expecting the occupancy survey to reveal stable temperatures but stuffy air quality — it did). The facilities management view is that the system could provide good occupant conditions, albeit at an unacceptably high cost. The facilities management team believes its role is to balance occupant demands with economic constraints.

Combining several highly technical systems such as ice storage and VVT into one building without a fully integrated control system means that the building staff have had a very steep learning curve. As the tenants took on the building and its relatively complex services sometime after initial commissioning they lost the benefit of the associated learning process, although they did retain the original m&e consultant's assistance for two years after building handover.

Comparison with the original specification

The building at 1 Aldermanbury Square, as it is currently being operated, diverges from the original specification in some vital respects, *writes Brian Warwicker*.

First, the current cooling loads are significantly less than those expected of the original design. These were 15 W/m^2 for lighting (actual 12 W/m^2), 7·5 m^2/person (actual 27 m^2/person) and equipment 30 W/ m^2 at 21°C or 60W/ m^2 at 23°C (actual 7 m^2 for an undisclosed temperature).

Second, the decision to run the air supply at a higher temperature than that originally specified inevitably results in higher air volumes and thus greater energy consumption by the main fans. Thus any free cooling calculation must involve a comparison of refrigeration energy versus fan energy to see which would be more economical.

It is often argued that CO_2 output is higher at night, but this is questionnable as nuclear power provides a much higher percentage of the baseload during off-peak periods, and therefore there is a saving on CO^2 per kW and also a saving on transmission losses.

Similarly, the conclusion that savings in electricity costs could be achieved by changing to a flat rate tariff ignores the fact that the system is not being used correctly, and the air supply temperatures are completely different. Therefore the operational changes suggested by the PROBE investigators are not relevant.

It is vital to note that the operation of the ice storage system was based on six tanks in operation not eight, the remaining two tanks being extra capacity should the design cooling loads be exceeded. In this case the two spare tanks would be charged at weekends.

The hydraulic arrangement of the common chilled header allows many modes of operation. It can either be chiller or ice-led, or chiller upstream/downstream. The original design was also for either the ice banks or the chillers to cater for 60% of the load (9500 kWh) which means that for the majority of the year, dependent on the tariff, the operator may choose to use either the ice store or the chillers.

Despite the system being designed for six tanks in use, all eight tanks are being exhausted of ice. This means the chilled water circuit is heating up, adversely affecting subsequent (night-time) attempt to build ice. This can only happen if the chillers are held off too long during the day, leaving the ice store to handle a greater proportion of the load — something it was not designed to do.

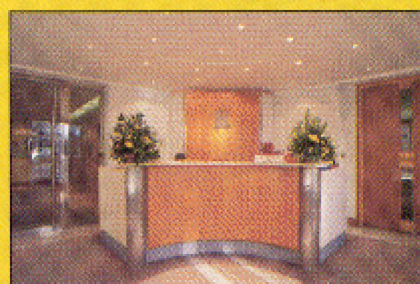
The flexibility designed into the ice system is not being used and this, combined with the failure of the operators to understand low temperature air conditioning, is the significant finding of this PROBE investigation.

key design lessons

Procurement For speculative developments system operation should be reappraised once the tenant's needs are known. This is particularly so for unusual services such as ice storage. Ideally, the original designers should help to develop an appropriate control strategy in order to minimise energy running costs – including power supply charges – while maintaining the required service and then help to implement and monitor it.

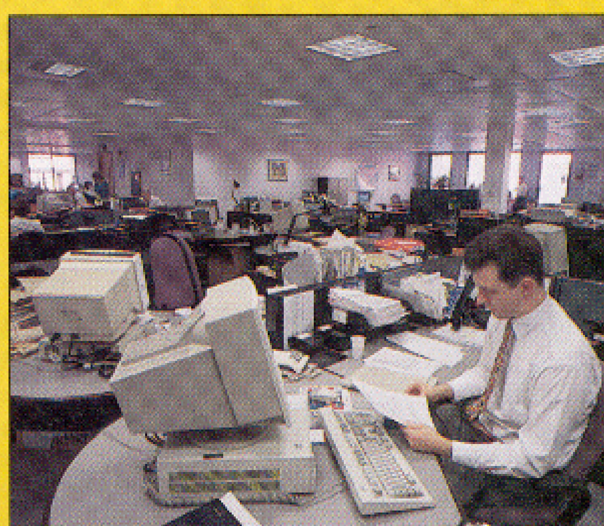
Planning restrictions on height led to the use of ice storage at 1 Aldermanbury Square.

Water problems Quantities of water form puddles on the floor between the ice tanks – water tests suggest that this is not ground water, nor glycol-treated chilled water. It is thought most likely to be from condensation as a result of poorly vapour checked tanks, spaced too closely to allow human access. A drainage channel cut into the slab could have prevented this.



The reception area is now enclosed to improve comfort conditions for staff and visitors.

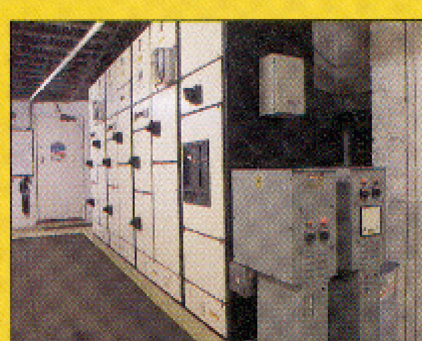
Reception area In late 1994 the reception was enclosed and a lobby created to improve comfort conditions for security staff and visitors alike. This appears to be a widespread problem for buildings endowed with grand reception areas.



Spot tests by the PROBE team confirmed that the lighting provides 350-500 lux on the working plane. At 36 kWh/m², the lighting energy consumption is low by typical 1980s standards.

Ice storage Chiller capacity is 25% smaller than the installed ice tank capacity, and so full ice charge during the 7 h off-peak period is impossible. The ice store also results in at least a 30% increase in electricity consumption for cooling compared with a system without storage, mainly due to lower efficiencies during ice charge, storage heat losses and extra pumping.

Chiller operation On-peak chiller operation should be minimised and completely avoided during the months of highest demand charges (November to February). Also, the practice of on-peak chiller operation to make ice when the off-peak period is insufficient should be avoided due to efficiency losses and high unit electricity costs.



Power supply In order to pre-empt low power factor penalties, power factor correction of 100 kVA capacity has been installed, helping to cover the entire electrical supply. Originally there was no provision for power

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References

[1]Brister A. "Melting away the costs", *Building Services.* April 1990. pp 22-26.

[2]Energy Efficiency Office. *Energy Consumption Guide 19.* EFO. October 1991.
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