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CENTRAL CHILLED WATER PLANT– BALANCING COMPETING ESD CHALLENGES

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Abstract

The central plant upgrade at the Victorian Arts Centre in Melbourne includes energy efficient design, including 12,000 kWr of new chilled water plant and associated infrastructure and controls.

Keywords: Environmentally Sustainable Design, Variable Speed Drives, Chillers, Load Efficiency, Energy, Chilled Water, Legionella Risk Management

- Protection of the ozone layer with compliance to the Montreal Protocol CFC/HCFC phase-out programme.
- Reduction of global warming emissions to support the Kyoto Protocol objectives.
- Legionella risk management.

From a review of projects presently in design and construction it appears that energy efficiency and reduction of greenhouse gas emissions are taking a lower priority than might be anticipated.

The Victorian Arts Centre (VAC) Central Plant Upgrade Project was principally designed to achieve high energy efficiencies and system availability. Legionella risk management and the protection of the ozone layer were also seen to be of critical importance and were addressed through an integrated approach to balancing all required key outcomes.

Completed in June 2000, the VAC Central Plant Upgrade Project involved:

- replacement of the centre's CFC based chiller plant and condenser water systems.
- replacement of the supporting electrical services infrastructure.
- implementation of a new LON based open protocol Building Automation System (BAS).

Serving the Melbourne Arts Precinct, which includes the Melbourne Concert Hall, State Theatre and the National Gallery of Victoria, the central energy plant provides 12,500kWr of peak cooling capacity and is one of the largest CFC replacement projects of its type undertaken in Australia.

Key outcomes sought by the VAC included:

- Replacement of the CFC chillers with new higher efficiency non-CFC chillers,
- Management of the water treatment issues, particularly those associated with the mitigation of Legionella risk,
- Reduction in greenhouse gas emissions and a significant contribution to the VAC's commitment to meet the Victorian State Government's Energy Efficient Government Buildings program energy consumption reduction target of 15% over a 5 year period.
- Removal of system single points of failure to support the National Gallery of Victoria's International Art Loan Agreements.
- Rectification of the chilled water system distribution performance problems.
- Life cycle optimised capital, energy and operation costs.

The project offered the single greatest opportunity to reduce the facility's energy consumption and global warming impact since its original completion some thirty years ago.

In reviewing the concept design for the project, key decisions were identified to be:

- Selection of a water-cooled or air-cooled based system, particularly given the issues associated with Legionella in Victoria.
- Whether to permit the use of R123 in addition to R134a given the balance of environmental factors, R123 toxicity and the HCFC phase-out programme.
- Chiller procurement strategy to be based on a traditional specification and schedule of chillers or a chiller system request for proposal.

The following provides an overview of the key assessment processes and lessons learnt from the project.

Air-cooled vs. water-cooled system selection

Whilst the project was designed and commissioned prior to the recent introduction of the new Victorian Government Regulations covering cooling towers and condenser water systems, consideration was given to the elimination of the Legionella risk via the use of air-cooled chiller plant.

Issues identified with respect to the implementation of an air-cooled plant were electrical infrastructure and chiller capital cost, energy costs and greenhouse gas emissions, spatial requirements, condenser coil corrosion and noise.

The choice between the two system types was principally determined by energy efficiency and Legionella risk management considerations.

Evaluation of the energy performance of air-cooled vs. water-cooled systems identified the following key points:

Full Load Efficiency Penalty

Large air-cooled chillers would achieve full load Coefficients of Performance (COPs) in the range of 2.8 to 3.0 kWr/kWe. This compared to adjusted (including for condenser water and cooling tower energy) water-cooled chiller system full load COPs in the range of 5.5-6.0kWr/kWe. The air-cooled system full load efficiency was almost half that achieved by the water-cooled systems.

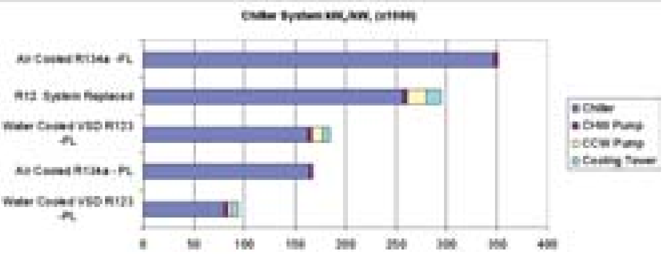
This efficiency gap leads to additional costs associated with energy consumption, maximum demand charges and electrical infrastructure. It was calculated that the additional electricity maximum demand charge based on design capacity to be of the order of $96,000/annum alone.

Part Load Efficiency Penalty

Part load performance is often sighted as a more important assessment criteria than full load energy efficiency due to the limited number of hours that the system operates at design capacity. Assessment of the part-load performance indicates that the efficiency advantages of water-cooled chillers remain substantial during most times of the year in temperate climates such as Melbourne's.

Estimation of the annual energy consumption cost saving was in the range of $170-200,000 per year. The estimated reduction in greenhouse gas CO_2 emissions based on Victorian brown goal electricity production (1.373 kg of CO_2 produced per kWh) was of the order of 60,000 tonnes per annum.

Chart 1: Chiller Efficiency for Full Load (FL) and Part Load (PL) Performance.



On the basis of substantial capital and ongoing operating costs penalties associated with air-cooled systems, it was determined that water-cooled would be preferred provided that the Legionella risk management criteria could be addressed satisfactorily.

Having clearly identified the costs avoided with a decision not to proceed with air-cooled systems, it was recognised that a higher level of expenditure to mitigate the condenser water system Legionella and corrosion risks through appropriate selection of cooling towers, chillers, water treatment systems and pipe materials was appropriate.

Specific strategies adopted to reduce the Legionella risk included:

- Selection of cross flow cooling towers in lieu of forced draft towers.(1)
- Full design Condenser Water (CCW) flow through operating cooling towers and chillers to reduce fouling and wet/dry boundary zones within the tower fill.
- ABS pipework throughout in lieu of mild steel to assure long-term effectiveness of the water treatment and reduce the problems associated with statutory system disinfection procedures.
- Pre-treatment of make-up water by the water treatment system.
- Circulation through the cooling tower balance lines.
- Side filtration and cooling tower basin sweeping system to remove suspended solids.
- Condenser water circulation cycles for idle equipment.
- Reduced condenser water temperatures whenever achievable.

The most important of these strategies was to lower the condenser water system temperature whenever possible below the critical range at which Legionella can become virulent.

Water Temperature	Legionella Growth Profile
below 20°C	dormant
20 – 25°C	virtually dormant although very slow growth is possible
25 – 30°C	slow growth if other factors are satisfied
30 – 43°C	heat shock mechanism changes Legionella metabolism so it may become virulent
37 – 43°C	most dangerous temperature range
45°C	maximum temperature for growth
46°C	stationary phase (dies over say 1 week)
50°C	dies slowly (say 10 hours)
55°C	dies in less than one hour
63°C	"official" kill temperature – Legionella dies in a few minutes
70°C	dies in seconds

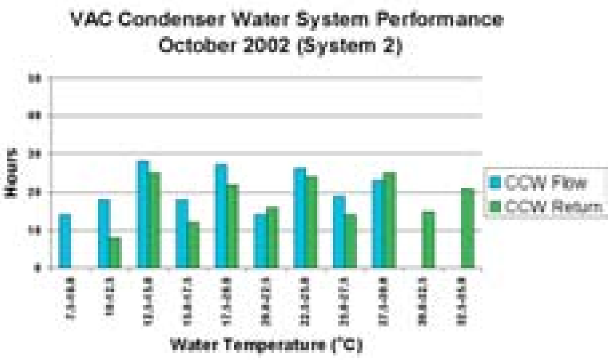
Table 1: Dependence of Legionella pneumophila on water temperature for growth.(2)

Points worth noting from this table are that:

- Below 25ºC the Legionella is virtually dormant
- Below 30ºC Legionella growth is slow

The following chart from the Building Automation System (BAS) Engineering Report indicates the performance of Condenser Water System 2 for the month of October 2002.

Chart 2: VAC Condenser water system performance – October 2002



Notes:

Maximum ambient temperature was 29.7ºC whilst the minimum ambient temperature was 8.3ºC

The low energy cooling towers with their higher capacity to maintain water temperatures typically within 5-10ºC of the ambient wet bulb temperature considerably lower the risk of a Legionella outbreak, particularly during the historically high risk spring and autumn periods.

It would appear reasonable to assume that even when condenser water temperatures do rise to the critical temperature range of 30 – 43ºC the risk is still reduced by the large number of hours when the biocide systems are working more effectively against Legionella surviving within the dormant temperature range.

Another important strategy of note has proven to be the pre-treatment of the condenser water system make-up water to reduce the infection rate of the system by Legionella naturally occurring in the water supplies.

With these measures an acceptable level of risk was assessed to be provided.

Refrigerant selection: HCFC vs. HFC

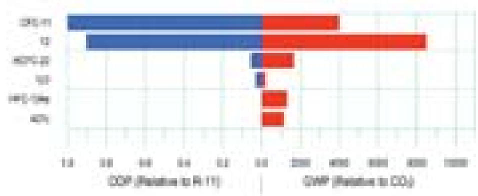
Initial project feasibility studies were prepared on the basis that R134a centrifugal chillers would be used; this initial decision being based on the perception that R134a was the safest environmental and political choice.

During the concept design phase it was decided to review the choice of refrigerants for the project. The benefits of R123 chillers became apparent from both an energy efficiency and capital cost perspective. Analysis indicated the decision to allow R123 centrifugal chillers would realise higher efficiencies in the range of 15-20% as well as lower chiller capital costs of the order of 15-20%.

A review of the environmental and HCFC phase-out issues associated with R123 was subsequently requested by the VAC.

Chart 3 indicates the relative ozone depletion and global warming potential of the common refrigerants in commercial HVAC system use.

Chart 3: Refrigerant Environmental Impacts (3)



Points from the table worth noting are that:

- CFCs warrant control both as ozone depleters and greenhouse gases.
- Only one refrigerant offers very low (near zero) ODP and GWP, namely R123.

Rigorous scientific analyses show that the impact of R123 chiller applications on ozone depletion are negligible, with less than a 0.001% peak contribution prior to the anticipated recovery of the ozone layer(4).

Further it was noted that:

- Refrigerant only becomes an issue to the ozone layer once it has escaped to the atmosphere: with high efficiency purge units, containment systems and leak monitoring, emissions from new R123 chillers are generally minimal and therefore result in negligible environmental impact.
- With the reinvestment of capital cost savings offered by R123 chillers a range of other energy efficiency measures can be implemented to further improve the overall efficiency and performance of the system.

As an interim refrigerant, the phase-out of R123 had to be considered. R123 is not scheduled for phase-out until 2030 and there is a commitment not to bring forward the current phase-out program dates. It is intended that R123 equipment be supplied under the Montreal Protocol Program until at least 2015 with service quantities anticipated to be available for several more decades after that.

On the issue of toxicity, R123 presents a relatively low risk, whilst R123 is classified as a B1 refrigerant it is worth noting:(5)

- The acceptable R123 exposure limit was increased to 50 PPM in 1997, with typical plant room refrigerant levels with current chiller technology and refrigerant management systems holding the refrigerant concentrations within plant rooms below 1 PPM.

- R123 presents a lower risk than R11 which it replaces on all three key short term exposure measures: anaesthetic effects, LC50 and cardiac sensitisation.
- HFC 134a has a higher cardiac sensitisation factor than R123.
- The risk of asphyxiation with negative pressure R123 is significantly reduced compared to high pressure refrigerants such as R12 or R134a.

To address the toxicity risks, a multi-point refrigerant detection system, breathing apparatus and an on-site refrigerant management system were provided.

There were no compelling reasons not to permit the use of R123 on the project and to realise the energy efficiency and capital cost benefits.

The result of this decision was in effect to reduce the chiller tender field down to two chiller suppliers with the two R134a only chiller suppliers declining to submit a proposal.

Chiller procurement and selection

Chiller procurement is typically based on a schedule of nominated chiller capacities, Integrated Part Load Values (IPLV) efficiencies and technical requirements. This is particularly the case where the chillers form part of the Mechanical Services Works Package. This approach however often does not allow suppliers to optimise their offers to suit a particular application.

An alternative approach was therefore adopted utilising a Request for Proposal to the chiller suppliers to provide their optimum chiller system to meet the project requirements. Information provided to the prospective chiller suppliers included:

- system performance requirements including minimum and maximum design capacities and plant redundancy provisions
- chiller staging and control strategies
- minimum energy performance standards
- technical and quality assurance requirements
- Summer, shoulder and winter system load profiles, chilled water temperatures and anticipated condenser water temperatures
- Extended comprehensive maintenance agreements (used to assess the true long term ownership costs).

It was anticipated that the proposals would provide either a combination of low load screw R134a and higher capacity R123 centrifugal chillers or a combination of Variable Speed Drive (VSD) and Constant Speed Drive (CSD) centrifugal chillers. Both configurations were offered with the following proposal being selected:

- 3 VSD R123 high efficiency open drive 2400 kWr chillers
- 3 CSD R123 high efficiency open drive 2550 kWr chillers

This arrangement provided both lower chiller capital and energy costs compared with the more traditional screw/centrifugal configurations.

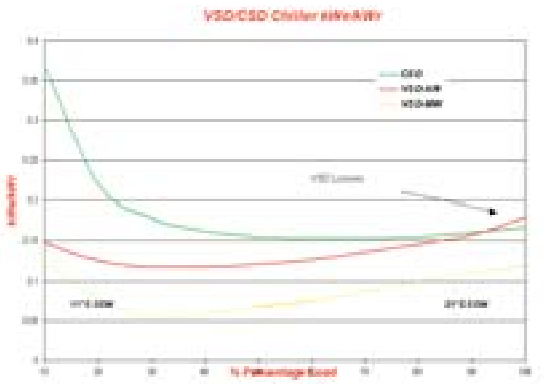
The benefits of the VSD chillers formed the basis for the development of an integrated design solution to address the project objectives and the chilled water system characteristics.

VSD R123 chillers

The VSD chiller controls incorporate three key components:

- Variable Speed Drive to operate the compressor at the lowest possible speed to achieve the capacity whilst maintaining stable operation.
- Inlet guide vane control to provide further capacity reduction below the minimum speed turn-down ratio.
- Advanced controllers that “learn” the individual chiller characteristics and continually seek to optimise its performance.

Chart 4: R123 VSD/CSD Chiller Performance.



Notes in relation to the chiller performance curves shown:

- The VSD ARI curve is based upon American Refrigerant Institute IPLV performance test parameters.
- The Melbourne Winter (MW) curve indicates expected winter low load chiller performance based on manufacturer’s published performance curves and typical condenser water temperatures available.

Key points to note include:

- There is a slight loss of chiller full load efficiency due to the switching losses associated with the VSD.
- The stable energy efficient performance offered by the VSD chiller extends well past the typical maximum turndown

ratios expected for most conventual chillers.

- The ability to use the lower condenser water temperatures to achieve extremely high COPs in the range of 10-15 kWr/kWe.

The benefits of this chiller technology with respect to the system design include:

Ability to use very low condenser water temperatures

With the cooling towers generally able to maintain condenser water temperatures within 5-10ºC of the ambient Wet Bulb temperature, condenser water temperatures are often held in the range of 12-20ºC over the winter and shoulder seasons. These low condenser water temperatures provide ultra-high coefficients of performance in the range of 10 to 15 kWr/kWe.

Lower overall project cost

Whilst the VSD chillers are more expensive per kWr than standard CSD chillers, they can result in an overall lower chiller system cost due to there being no requirement for dedicated low load chillers and their associated piping, electrical and controls infrastructure.

High chilled water flow whilst maintaining high chiller efficiency

The chiller offers the ability to handle the problem of low return chilled water temperatures common in many large systems operating at low loads. The chiller provides higher flows and thereby delays the start of a second chiller – operational experience has indicated that the VSD chiller operating as the low load chiller operates for extended periods at 20-30% load whilst maintaining a chiller COP in the range of 10-15.

Simplified chiller staging

Staging of the chillers is via a single magnetic flow meter across the primary/secondary decoupler line. There is no check valve in the decoupler line allowing both positive and negative flow. This control strategy assures stable and accurate chilled water system leaving temperature control is maintained to the NGV environmental control systems secondary pumping system.

Simplified condenser water system control

Control of the low energy cooling towers is straightforward with the chillers able to accept almost any condenser water temperature. There are no limitations imposed on return condenser water temperature by either screw or reciprocating chiller requirements to maintain a minimum condenser water temperature typically in the required range of 20-29.5ºC.

Open drive energy efficiency gains

Being open drive, the chillers require the cooling towers to reject some 10-15% less heat. With the plant located in the basement it has been found that the built environment acts as an adequate heat sink to absorb the motor heat rejection.

Reduction in Legionella risk

The ability of the chillers to operate at condenser water temperatures below which Legionella can multiply, particularly during the higher risk shoulder seasons, greatly reduces the risk of Legionella becoming virulent.

Greater capacity on standby power supplies

With the chiller VSD drive able to limit the inrush current to its FLA, the chillers are able to start more easily on generator-fed supplies without tripping on voltage drop. This has greatly increased the cooling capacity available during standby power operation.

Condenser water system energy initiatives

The initial project feasibility studies were based on forced draft cooling towers with the principal aim to reduce floor plate area.

Six low energy cross-flow towers were ultimately selected due to their significantly reduced energy requirement and lower Legionella risk factor (1). Overall a reduction of 50% in the fan horsepower was achieved by changing the cooling towers from forced-draft to cross-flow at equivalent capital cost taking into account the deletion of the attenuation requirement applicable to forced draft units.

Simple two speed fans, high efficiency motors and aerofoil blades lower the energy consumption as well as reduce noise levels.

Assessment of the compressor efficiency and cooling tower performance indicates that it is preferable to operate cooling tower fans to minimise the leaving condenser water temperature with the fan only staging down as the condenser water temperature approaches the minimum chiller condenser water-chilled water approach temperature requirement of 5-6ºC.

Use of variable speed drives on the condenser water pumps in lieu of modulating flow limiting valves to maintain a constant condenser water flow across the chiller was found to save both capital cost and energy.

The two condenser water systems, each with three cooling towers serving three chillers are constructed almost entirely of ABS pipework. Whilst ABS is generally thought to be too expensive for building services applications, careful design of the system as part of an integrated solution allowed it to become cost effective.

A side filtration and an Electro-Magnetic Radiation (EMR) water treatment system was installed to manage biological growth, maintain heat exchanger energy transfer efficiency and control corrosion. Use of the non-chemical based water treatment system was implemented as part of the overall ESD philosophy to reduce toxic chemical emissions to the environment. The system proved to be generally as effective as a chemical system based on the Heterotrophic colony counts (HCC) and Legionella test results achieved. The system however did not appear to be able to provide effective protection of the marine boxes against copper induced galvanic corrosion, despite impressed current protection systems also being installed. It was subsequently necessary to provide a chemical-based copper corrosion inhibitor system to address this issue. It has also been necessary to implement a chemical based biocide system with the introduction of the Victorian Government Health (Legionella) Regulations requiring installation of traditional chemical-based biocide systems and regular disinfections.

Chilled water system energy initiatives.

A number of chilled water system energy initiatives were implemented including:

- use of lead/lag variable speed secondary pumping systems (with third standby), high efficiency pump control strategies and pump selections;
- decoupling of chilled water loops with different pump duty requirements allowed a reduction in total pump kW. Whilst there are some instances where a primary only variable flow system may reduce the overall pump energy, where significant differences in pump duties are required between different loops then the savings for a primary/secondary system can increase rapidly.
- Flushing of the chilled water distribution system using the duty and standby pumps operating in parallel to achieve approximately 130% of design flow with lifted material removed via the side-stream chilled water system centrifugal separator and coil strainers.
- Rebalancing of the chilled water loops, identification of the true index coil and minimisation of the system DP setpoint, removal of remaining three-way control valves and cleaning of strainers

Environmentally Sustainable Design Conclusions

The design of optimised central plants is important because the outcomes impose energy and environmental commitments for 30-40 years. Today's challenge is to optimise a range of competing ESD objectives; to do this effectively requires:

- Better environmental and legislative frameworks with more stringent minimum energy performance standards and greater recognition of the requirement to optimise across a range community and environmental objectives. Reliance on market forces to deliver energy efficient design is but little more than wishful thinking – particularly when in most cases the payment of energy costs are offset to a third party tenant.
- Greater focus on design optimisation rather than first acceptable solution to allow completion of the documentation process within the ever-decreasing design programmes being allowed.
- Better energy analysis tools requiring greater involvement by key product suppliers.

Engineers and designers have a key role to play in educating stakeholders including developers, owners and tenants to recognise the benefits of a triple bottom line approach and what this may require in terms of time and commitment.

Conclusions

The outcomes of the project and observations of recent industry trends lead to the following conclusions:

- It is time for the phase-out of R123 centrifugal chiller applications to be removed from the Montreal Protocol phase-out programme.

  The Montreal Protocol has been an outstanding success with indications that the ozone layer is now in recovery(6). However, there is a fundamental flaw with the current Montreal Protocol in that it is based on classes of refrigerants as the basis for implementing phase-out programmes and does not adequately consider global warming costs associated with its implementation. Further it is not able to differentiate between the benefits and costs associated with different refrigerant applications.

  The unfortunate early casualty of this is that designers have largely turned away from this refrigerant and are opting for R134a. R123 was promoted in the 1990s as the balanced environmental refrigerant of choice. This remains the case today and even more important with global climate changes becoming a harsh reality and brown-out restrictions becoming a common problem as the nation's electrical infrastructure struggles to meet peak summer cooling loads.

- Compliance with statutory Legionella risk management guidelines should be deemed as discharge of duty-of-care.

  There is no doubt that issues associated with the management of Legionella and corrosion within cooling tower/condenser water systems requires careful consideration. In specific circumstances the risks associated with these systems cannot be tolerated, however for the majority of commercial and government projects they can be reduced to an acceptable level within the Government Health Regulations. Appropriate risk assessment, engineering and operational practices including preparation of risk management plans should be able to be relied upon by those involved to fully discharge their duty-of-care and responsibilities to the community.

  Engineering risk management is widely accepted practice and forms the basis of almost all design involving public risk and cost. There should be no reason that it cannot be applied effectively to the use of condenser water systems.

Best practice also dictates that the risk management process begins with design and not the preparation of a risk management plan only once the system is about to be put into service, indeed the preparation of the risk manage

and the science and practice of Legionella risk management should also be reviewed so that engineering risk management does not effectively become zero-tolerance in practice.

- There is a need for the chiller and cooling tower suppliers to develop an industry accepted engineering energy simulation model that can be relied upon to accurately assess the comparative performance of chiller/cooling tower systems proposals with the view that it also form the optimisation software engine for proprietary chiller/condenser water system controllers.

Key stakeholders deserve better than the current reliance on ARI IPLV or NPLV numbers to compare and evaluate alternative chiller system proposals. These chiller efficiency rating systems are empirically based and provide relatively poor performance assessments and optimisation tools for projects like the VAC Central Plant Upgrade.

It would be reasonable to expect that the leading chiller suppliers are better able to analyse chiller/condenser water system performance than the current energy modelling programmes given their detailed knowledge of the chiller performance. It would also be reasonable to expect that these chiller system controllers should be able to optimise the performance of the system better than BAS systems which tend to operate on relatively simple control logics. Neither capability was able to be demonstrated adequately in the requests for proposal submissions received.

Proprietary chiller/condenser water system control software should include both adaptive learning and fuzzy logic algorithms (6) to optimise the system performance against the complex range of independent system variables and plant performance characteristics. These types of programmes are now commonly applied to many engineering systems from automobiles to German front loading washing machines and can deal with complex optimisation problems.

Chiller/condenser water systems could deliver significant energy benefits from the application of this type of control.

The design outcome of the VAC central plant project challenges many traditional design wisdoms in relation to chiller plant design as well as the recent trend to very large air-cooled systems for commercial projects. It strikes an acceptable balance across the competing objectives that can be argued delivers a triple bottom line that will stand the test of time.

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