NH_3 FOR AIR CONDITIONING – FACT OR FICTION?

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ABSTRACT

This paper describes the application of ammonia as the primary refrigerant in a large scale air conditioning system servicing a local Council administration building in South East Queensland, Australia. The new NH_3 based air conditioning system replaces two HCFC 22 based air conditioning systems. The secondary refrigerant is reticulated chilled water. The new plant incorporates energy recovery by means of discharge gas desuperheaters.

1. INTRODUCTION

Australia is a signatory to the Accelerated Freeze and Phase-Out of Ozone and Climate-Damaging Chemicals agreed during the Montreal Protocol's 20th Anniversary Celebrations in September 2007. Importation of HCFC22 into Australia has been phased down and consumption must reduce by 90% by 2015 with final phase-out by 2020.

During the lead-up to the final passing of the Clean Energy Bill in the Australian Senate on the 11th of November 2011, many refrigeration plant users in Australia explored ways of minimizing the impact of this new legislation. Not only does the legislation assign a price on carbon pollution, it also includes a special levy on hydrofluorocarbon (HFC) refrigerants. The latter increases the retail price of HFC's by 300 to 500%.

These environmental measures are having an increasing impact also on the commercial, large scale air conditioning industry. Commonly used liquid chilling packages with HFC charges of several hundred kilograms are being significantly disadvantaged commercially due to the special HFC levy. Replacement charge costs ranging in the several hundred thousand Dollars for R134A chillers will not be uncommon in the future.

As an example, a water chilling package for air conditioning with a cooling capacity of around 1500 kW, centrifugal compressor and shell and tube heat exchangers manufactured around 1970-80, may be considered. The R134a charge would typically be 3000-3500 kg. The published list price for R134a effective 9 July 2012 from one wholesaler is \$181.82/kg. The list price of a replacement refrigerant charge would therefore be in the vicinity of \$550,000 to \$650,000. Even with allowances for trade discounting, the commercial risks associated with leakages become very significant. The Department of Sustainability, Environment, Water, Population and Communities has published a Calulator for the Import Levy and Equivalent Carbon Price for SGGs and SGG/HCFC Blends. This calculator nominates the total levy for refrigerant R134a at $30.07/kg. In this example, the HFC levy payable would therefore be $90,000 to $105,000 plus refrigerant costs, plus supply chain margins plus labour charges.

The paper details the design, implementation and operating experiences associated with a 1200 kW reticulated chilled water air conditioning system installed in a local Council administration building in South East Queensland. The new plant replaces two air-cooled HCFC 22 based air conditioning systems.

The paper shows predicted annual energy savings of around 35-50% and details the methodology employed during the evaluation of these. Comments in relation to projected annual maintenance costs are included to enable readers to make comparisons with equivalent HFC installations including post 1.7.2012 projections.

2. BACKGROUND

In November, 2009 Logan City Council invited tenders for the provision of Solar Air Conditioning and Solar Hot Water Systems for the Logan City Council Administration Building. In connection with this request for tender, a site inspection was arranged by Council staff for contractors interested in submitting bids.

During this site inspection it became evident that the Council was open to technical proposals outside the specific tender scope provided these would meet the Council's overall objective of reducing its carbon footprint.

It is outside the scope of this paper to detail the technical concepts of the wide variety of bids received. These may be found in [1]. The winning bid sought to address two fundamental issues associated with the existing air conditioning systems. These were:

- the employment of refrigerant HCFC 22, which is currently being phased down,
- the relatively poor energy efficiency of fixed speed drive, air cooled systems compared with more modern, variable speed drive, water cooled systems employing natural refrigerants.

By substituting HCFC 22 with a natural refrigerant, the rising costs associated with replenishing refrigerant lost as a result of system leakage would be mitigated. At the same time, the significant global warming impact associated with fugitive gases would be eliminated. Secondly, substituting existing air cooled HCFC 22 based water chillers with more efficient water cooled systems employing variable frequency drive compressors would significantly reduce power consumption and hence greenhouse gas emissions. A reduction in air conditioning plant power consumption would reduce the capital costs associated with future integration of photovoltaic solar panels for the provision of electric drive power for the new air conditioning system. The latter is an investment that the Council may consider at a later date.

In summary, the winning concept may therefore be viewed as forming part of a number of development stages designed to gradually reduce the carbon footprint of the existing office building. First stage is elimination of an environmentally harmful refrigerant. Second stage is reduction of power consumption to pave the way for renewable energy supply. Third stage is the recovery of condenser heat from the new air conditioning system to eliminate/minimize the electric energy input into the building hot water systems.

3. THE HCFC BASED AIR CONDITIONING SYSTEMS

The two air conditioning systems being replaced by the new NH3 based, central air conditioning system both employ HCFC 22 as the primary refrigerant. HCFC 22, also commonly known as R22, is a refrigerant that is used widely in both air conditioning and refrigeration. It represents approximately 30% or around 12,000 metric tons of the “working bank” of chemical refrigerants currently in use in Australia [2]. Production of HCFC 22 commenced in 1944. Since that time more than 80% of the total quantity produced or more than 8,000 million metric tonnes of CO_2e has entered the atmosphere [3]. The larger of the two R22 systems is situated within a roof top plant room and comprises two air cooled water chilling packages, figures 1 and 2.

Chilled water is used as the secondary refrigerant for the air conditioning system. The chilled water is circulated from the plant room through the building air conditioning system by means of two chilled water pumps. These are also situated within the plant room.

Figure 1. Existing Roof Top Plant Room with Two Air Cooled Water Chillers and Chilled Water Pumps

Figure 2. Roof Top Plant Room Exterior

The smaller of the two R22 air conditioning systems is located within the basement of the building. This comprises two open, direct drive reciprocating compressors. These are both connected to a central air handling unit fitted with dry expansion cooling coils designed for cooling the air stream by direct evaporation of the primary refrigerant within the coil elements, figures 3 and 4.

Figure 3. Open Drive R22 Compressors

Figure 4. Air Handling Unit

The condenser is of the remote air cooled type mounted on the roof of the building, figure 5.

The air conditioning system design described and shown here is representative of a significant number of similar air conditioning systems in Australia.

Figure 5. Remote Air Cooled Roof Mounted R22 Condenser

The combined cooling capacity of the two systems in as new operating condition is around 1200 kW. The roof top mounted engine room accounts for around ¾ of the total capacity; the balance is serviced by the installation located in the basement. Physically, the roof top plant room and the basement plant room are around 90 m apart.

3.1 Energy Consumption

Between the 14th of December and the 22nd of December, 2009, the Logan City Council recorded the power consumption of the existing air cooled water chillers situated in the roof top plant room. Extracts of the records are shown in table 1.

#	Time, GMT+ 10:00	Blue phase Chiller 1	Blue phase Chiller 2	White phase Chiller 1	Chiller 1	Chiller 2	Temp & RH, inlet air to chiller plant			Cooling energy
		$I_{1,1}$	$I_{2,1}$	$I_{1,2}$	P_1	P_2	T_A			Q_E
		[A]	[A]	[A]	[kW]	[kW]	Temp. [°C]	RH [%]	COP	[kWh]
1	12/14/09 10:02:46 AM	281	112	287	196.2	77.1	29.9	56.7	2.86	
2	12/14/09 10:07:46 AM	252	140	258	175.9	96.5	29.5	57.8	2.87	65.2
3	12/14/09 10:12:46 AM	254	223	256	175.9	154.1	29.7	56.8	2.87	78.9
4	12/14/09 10:17:46 AM	279	221	285	194.5	152.2	30.1	55.2	2.86	82.5
5	12/14/09 10:22:46 AM	250	277	254	173.7	190.9	29.7	55.8	2.87	87.2

Table 1. Extract from Logan City Council measurement of existing chiller package power consumption.

The absorbed currents for the two chillers situated in the roof top plant room were recorded at five minute intervals. The equations used by Logan City Council for estimating the chiller power consumption are:

$$\text{Chiller 1: } P_1 = (I_{1,1}+I_{1,2})/2*3*230/1000, \text{ [kW]} \quad (1)$$

$$\text{Chiller 2: } P2 = I_{2,1}*3*230/1000, \text{ [kW]} \quad (2)$$

The equation used for estimating the chiller coefficient of performance (COP) is:

$$COP = 2.8+(32-T_A)*0.03, \text{ [-]} \quad (3)$$

Equation (3) is a simplified estimation of the chiller COP at ambient temperatures other than 32℃. The base COP at 32℃ ambient temperature is 2.8 according the manufacturer’s as new performance ratings. For every degree the ambient temperature reduces/increases, the COP is corrected linearly as shown in equation (3).

The equation used for estimating the cooling energy Q_E provided by the chillers during the time interval applicable is:

$$Q_E = (P_1+P_2)*COP/60*5, \text{ [kWh]} \quad (4)$$

The sum of the cooling energy delivered over a total of 2304 measurement intervals or 192 hours was measured at 72.5 MWh; the corresponding absorbed chiller energy was 24.6 MWh – average

COP 72.5/24.6=2.95. The average cooling capacity may therefore be calculated as 72.5*1000/192=377.6 kW. Extrapolating this to a full year yields an annual cooling energy requirement ΣQ_E of 8,760*377.6/1000≈3,308 MWh for the roof top plant room. The annualized cooling energy delivery from the basement plant room was simply included on a pro rata basis using the nominal maximum chiller capacities. Total cooling energy $\Sigma Q_{E,TOT}$ required to be replaced by the new air conditioning system:

$$\Sigma Q_{E,TOT} = \Sigma Q_E /(448*2)*(448*2+235) = 4{,}175 \text{ [MWh]} \qquad (5)$$

where 448 kW and 235 kW represent the nominal capacities of the roof top and the basement plant room chillers respectively.

4. THE REPLACEMENT AIR CONDITIONING SYSTEM

The replacement air conditioning system comprises two identical water cooled, low refrigerant charge water chilling units employing refrigerant ammonia (NH_3), figure 6.

Figure 6. SABROE HeatPAC Packaged Water Chiller employing NH_3 refrigerant

The compressors are of the industrial, open reciprocating type. The cooling capacities of the chillers are controlled by a combination of compressor speed control and cylinder unloading. A sophisticated proprietary control system determines the optimum combination of rotational speed and cylinder unloading ensuring maximum energy efficiency while minimizing the probability of resonance frequencies. The combined refrigeration capacity of the two units is approximately 1,200 kW. Each chiller is fitted with a shell and tube type discharge gas desuperheater. These heat exchangers recover heat from the discharge gas leaving the compressors prior to the gas entering the condensers. In the future, the heat recovered will be utilized for heating hot water and for various other purposes yet to be determined by the Council. The future heat recovery system is shown in figure 7.

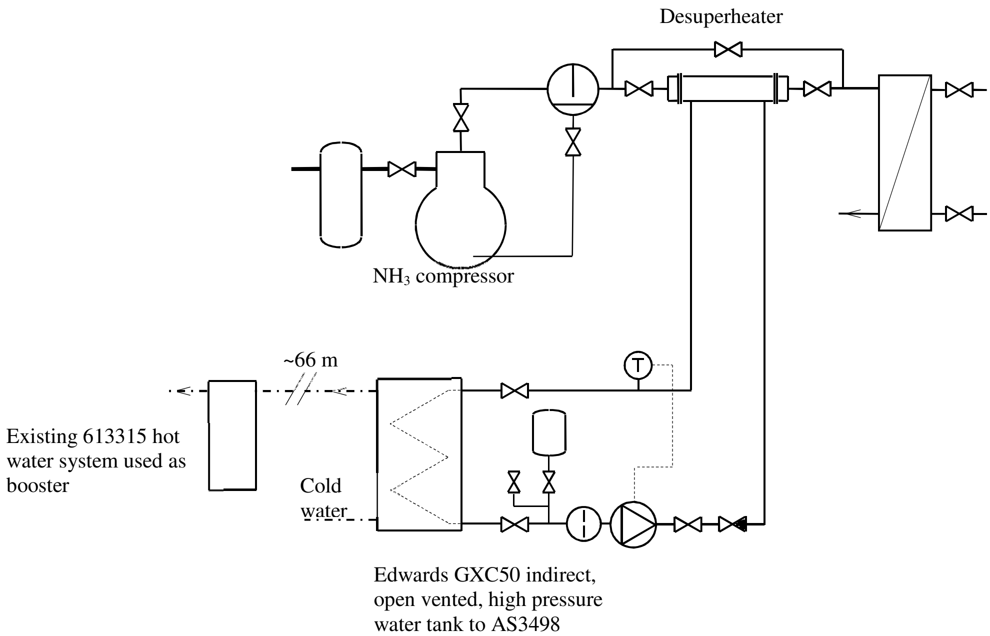

Figure 7. Future Heat Recovery System

Connection of the basement air handling unit to the replacement air conditioning system required replacement of the existing dry expansion type R22 cooling coils with new coils suitable for chilled water reticulation. In addition, new chilled water supply/return lines (CHW) needed to be run across the west and north wing roofs to connect the roof top plant room with the basement air handling unit, figure 8.

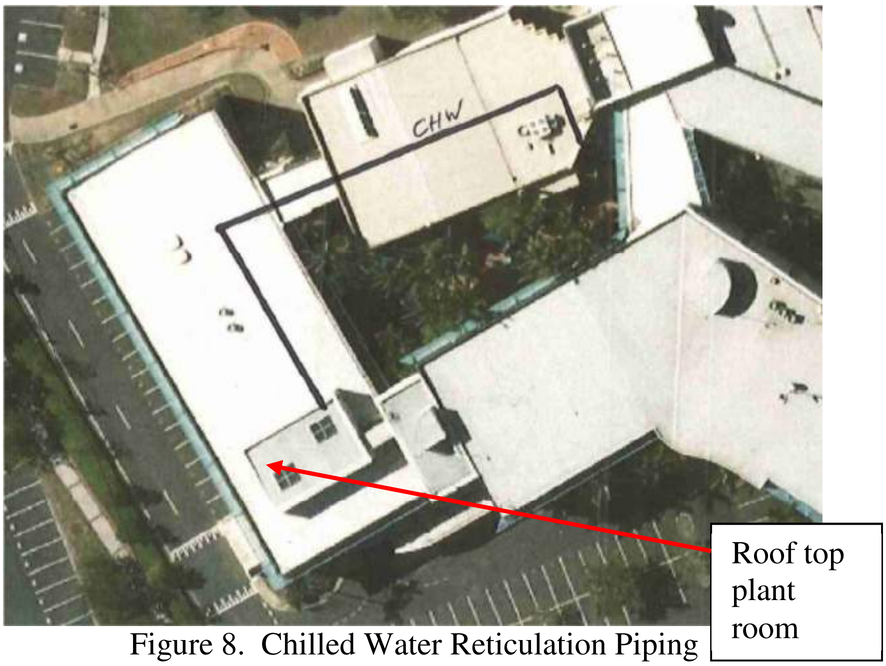

Figure 8. Chilled Water Reticulation Piping

The cooling towers are installed within the plant room enclosure. These towers draw air through the same air intake louvers that were used for the previous air cooled HCFC 22 chillers, figure 9. The total mass of the new equipment slightly exceeds that of the existing equipment. Floor deflection is being assessed and monitored by Council consultants.

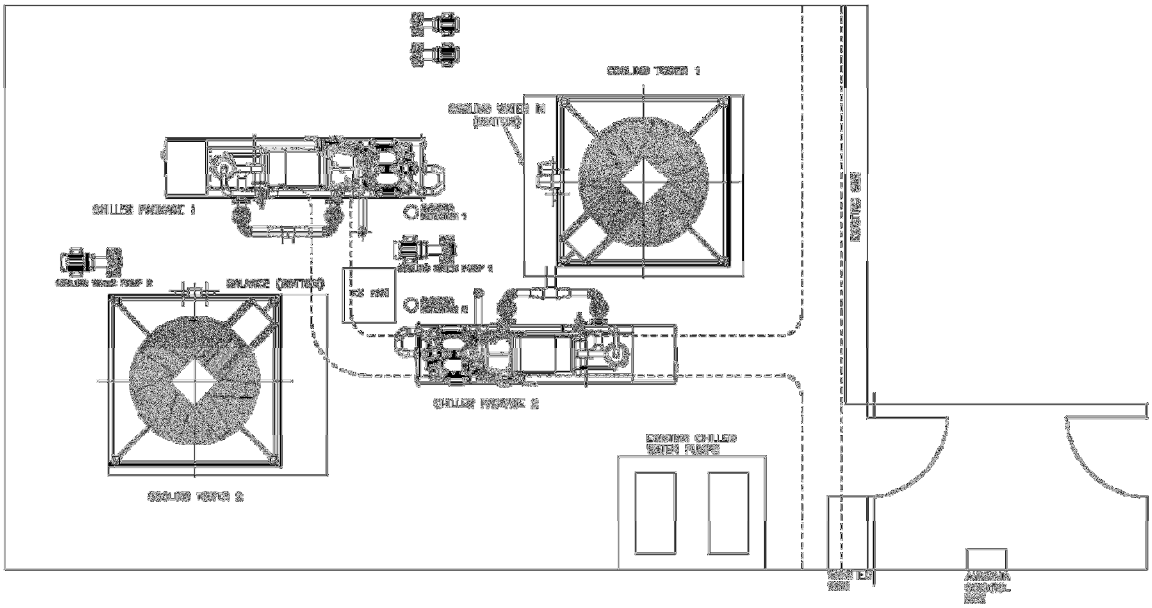

Figure 9. Plant Room Layout Showing NH_3 Chillers and Cooling Towers

Like any other employer, the Logan City Council has a duty of care with respect to ensuring a safe working environment for employees. Ammonia is toxic and also flammable in concentrations from 15 to 28% by volume (150,000-280,000 ppm) in atmospheric air.

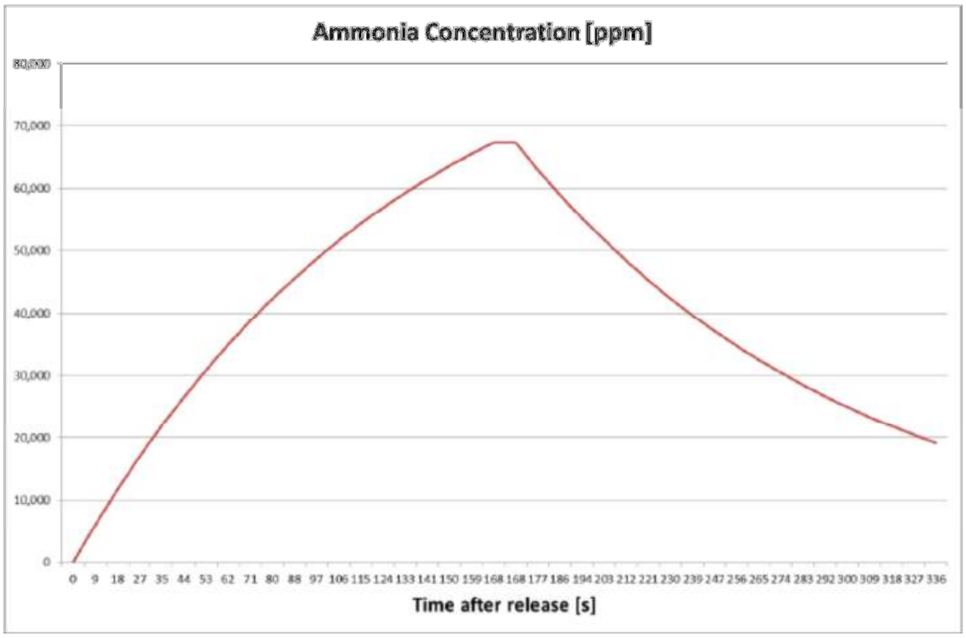

Figure 10. Ammonia concentration as a function of time in the event of a catastrophic release of an entire refrigerant charge (33 kg) in liquid form.

To analyse the potential fire risks associated with a catastrophic refrigerant release within the roof top plant room (room volume ~450 m³) and the actions necessary to mitigate that risk, Logan City Council commissioned an independent consultant to model the NH_3 concentration as a function of time in the event of a major release, figure 10. The worst case scenario contemplated was the instantaneous release in liquefied form of the entire refrigerant charge of one chiller (33 kg of NH_3). This is based on the assumption that only the emergency ventilation (3 m³/s) and not the cooling tower fans are operating.

Although the predicted peak NH_3 concentration of 67,400 ppm is well below the lower explosive level (LEL) of 150,000 ppm, it is above the 30,000 ppm (20% of LEL) nominated by the "Victorian Code of Practice for Ammonia Refrigeration 2011" as the concentration that initiates operation of emergency exhaust fans.

The recommendation following this modelling was to include the two cooling tower fans in the emergency ventilation logic. Each fan has a unit capacity of 19.2 m³/s. Applying the same modelling principles as those used for the preparation of figure 10, this additional ventilation rate reduced the peak ammonia concentration to <7,000 ppm hence eliminating the need for specially protected electrical equipment within the plant room. In this emergency situation, the cooling towers would also act as scrubbers. Ammonia is readily absorbed in water so the cooling towers would therefore further reduce the ammonia concentration in the air being discharged to the atmosphere.

4.1 Power and Energy Consumption

The three main incentives for replacing the HCFC 22 air conditioning systems are:

- Elimination of the reliance on R22 refrigerant, which is being phased out
- Reduction in connected power
- Reduction in annual electrical energy consumption

The reduction in power consumption and installed electric motor power are detailed below, table 2.

Using the nominal performance data in table 2, the full load coefficient of performance (COP) for the air conditioning systems being removed is (448*2+235)/(315.2+40.8+86.4+6.0)=2.52. The COP for the replacement system is (596.3*2)/(261.2+17.6+26.6+6.2)=3.83.

Equipment being removed	Installed Electric Motor Capacity	Peak Power Consumption	Apparent peak power consumption
	[kW]	[kW]	[kVA_r]
YORK YCAJ 66ST9:			
Compressors	364.0	252.0	315.2
Condenser fans	32.8	30.4	40.8
Carrier 5H40--149	74.0	65.6	86.4
Air cooled condenser fans	4.4	4.4	6.0
Total being removed	475.2	352.4	448.4
Equipment being added			
SABROE HeatPAC 108LR-A packaged water chillers	220.0	207.4	261.2
B.A.C. RCT 2176 cooling towers	15.0	13.8	17.6
Cooling water pumps	22.0	21.0	26.6
Chilled water pumps	11.0	4.7	6.2
Total being added	268.0	246.9	311.6
Total reduction	**207.2**	**105.5**	**136.8**

Table 2. Reduction in connected power and power consumption associated with the replacement of the existing HCFC 22 air conditioning systems.

The energy consumption measurements referred to in section 3.1 highlighted extensive periods where the air conditioning systems operate partly loaded. In these situations, minimization of annual system energy consumption requires selection of chiller units with good part load efficiencies and intelligent sequencing capability. This is well demonstrated by comparing the difference in IPLV (Integrated Part Load Value) between chiller units with and without compressor speed control, tables 3 and 4.

Q_E [kW]	P [kW]	$T_{i,E}$ [°C]	$T_{o,E}$ [°C]	$T_{i,C}$ [°C]	$T_{o,C}$ [°C]	Time [%]	η_{MOT}	COP
579.4	96.5	12.2	6.7	29.4	33.9	0.0	0.932	5.59
434.5	58.0	10.8	6.7	23.9	27.1	0.4	0.923	6.92
289.7	29.8	9.4	6.7	18.3	20.4	0.4	0.889	8.63
144.8	15.6	8.1	6.7	18.3	19.4	0.1	0.863	8.04
COP(IPLV)								7.81

Table 3. IPLV values for SABROE HeatPAC LR-A without VFD

Q_E [kW]	P [kW]	$T_{i,E}$ [°C]	$T_{o,E}$ [°C]	$T_{i,C}$ [°C]	$T_{o,C}$ [°C]	Time [%]	η_{MOT}	COP
608.9	99.5	12.2	6.7	29.4	33.9	0.0	0.930	5.69
456.6	56.2	10.8	6.7	23.9	27.1	0.4	0.930	7.55
304.3	25.1	9.4	6.7	18.3	20.4	0.4	0.930	11.27
152.3	14.1	8.1	6.7	18.3	19.4	0.1	0.930	10.07
COP(IPLV)								9.51

Table 4. IPLV values for SABROE HeatPAC LR-A with VFD

Legend:

Q_E	Refrigeration capacity	[kW]
P	Shaft power	[kW]
$T_{i,E}$	Water temperature evaporator inlet	[°C]

$T_{o,E}$	Water temperature evaporator outlet	[°C]
$T_{i,C}$	Water temperature condenser inlet	[°C]
$T_{o,C}$	Water temperature condenser outlet	[°C]
η_{MOT}	Electric motor efficiency	[-]

The IPLV values are calculated in accordance with ARI Standard 550/590. The NPLV's (Non-standard Part Load Values) for the actual load variation have not been calculated, but the IPLV values provide an acceptable illustration of the efficiency gains possible by means of variable reciprocating compressor speeds for capacity control.

Based on the annual cooling energy delivery from equation (5) and an average COP of the HCFC 22 systems of approximately 3, the combined annual electrical energy consumption of the HCFC 22 systems may be estimated at approximately 4175/3≈1400 MWh. Based on a full load COP improvement of the natural refrigerant based air conditioning system of (1-2.52/3.83)*100=34%, the annual reduction in electrical energy consumption may be estimated.

For the purposes of the Council's decision making process, this calculation of annual reduction in electrical energy consumption was simply carried out as 1400*0.34≈500 MWh. Any additional efficiency gains associated with the IPLV improvements illustrated in tables 3 and 4 were considered in the decision making process as a bonus.

The total installed cost of the new NH_3 based air conditioning system as described was around $1,000,000 as at the end of the 2010 calendar year. The estimated reduction in CO_2e emissions annually is 680 tonnes. This reduction represents a combination of reduction in electrical energy consumption and elimination of fugitive gases from the the existing HCFC22 systems. Based on a carbon price of $23/ton of CO_2e and a unit electricity charge of $200/MWh, the simple pay-back period for the investment is ~8.5 years.

Logan City Council did engage an independent refrigeration consultant for verification of the potential energy savings associated with the replacement of the HCFC 22 air conditioning systems. This verification was in broad agreement with the simple calculation described above.

4.2 Maintenance

To assist in the Council's decision making process, an estimate of the maintenance costs of the natural refrigerants based air conditioning system was prepared. This cost estimate covered the first 10 years following initial commissioning.

Annual maintenance plan, year 5:	Relative costs [%]
Monthly service visits	16
Annual water treatment averaged	17
Annual (or 5,000 hour) compressor service	26

Annual maintenance plan, year 5:	Relative costs [%]
Compressor service (40,000 hours) based on each compressor operating ≤5,000 hours annually	0
Operational faults, break-downs or other issues requiring the attention of a skilled technician (assumed 3 visits per month)	36
Consumables averaged	4
Oil PAO 68 averaged	1
Total	100

Table 5. Elements forming part of comprehensive maintenance cost estimate

The elements included in the estimate are detailed in table 5 using the 5th year after handing over as an example. The allowance for operational faults is deliberately very conservative. It reflects the relative inexperience of the Council maintenance staff regarding natural refrigerants (particularly NH_3), the relative novelty of the general application in the Australian market and the relative novelty of the electronic control and monitoring system.

Period	**NPV**
Annual maintenance costs year 2nd year after handing over	$40,555
Annual maintenance costs year 3rd year after handing over	$36,166
Annual maintenance costs year 4th year after handing over	$36,518
Annual maintenance costs year 5th year after handing over	$37,230
Annual maintenance costs year 6th year after handing over	$40,644
Annual maintenance costs year 7th year after handing over	$42,232
Annual maintenance costs year 8th year after handing over	$63,141
Annual maintenance costs year 9th year after handing over	$45,372
Annual maintenance costs year 10th year after handing over	$51,026

Table 6. Net present values for annual maintenance costs

The net present values (NPV) of the projected annual maintenance costs are summarized in table 6. These assume a consumer price index (CPI) of 3% p.a. with the calendar year 2010 as the base year.

5. CONCLUSION

Logan City Council decided to replace two existing HCFC 22 based air cooled air conditioning systems with a new, modern, water cooled air conditioning system employing the natural refrigerant ammonia (NH_3) as the working fluid.

Council gained a range of benefits from pursuing this project, including:

- No HFC Levy because the global warming potential (GWP) of ammonia is zero,
- reduction in the loss of fugitive gases – this represents a reduction of around 80 tonnes of CO_2e annually based on an annual leakage rate from the previous HCFC 22 systems of 9%,

- improvement in maximum chiller COP (Coefficient of Performance) from 2.52 to around 3.83 at full load when accounting for the influence of electric motor efficiencies,
- through the inclusion of variable frequency drives on the new NH_3 based chillers, the IPLV is predicted at 9.51; this is around 60-70% better than status quo,
- based on the new NH_3 based chillers providing a total annual cooling energy of ~4,200 MWh , the annual reduction in electrical energy consumption is estimated at ~500 MWh; using a unit electricity cost of $200/MWh this represents an annual cost saving of $100,000,
- potential to drastically reduce the energy consumption associated with the production of hot water in the future,
- integration of the basement air handling unit so that this may be supplied with chilled water from the new NH_3 based chillers. This ultimately results in total removal of environmentally harmful refrigerants from two of the Council's Administration Centre air conditioning systems,
- integration into the existing reticulated chilled water type air conditioning system without any major modifications to the plant and to the peripheral services such as engine room enclosure, electrical services, drainage and structures,
- significant reduction in north wing noise levels currently generated from the old basement chillers because the existing reciprocating compressors are removed from that area,
- reduced modification costs in any future upgrade to the north wing basement canteen area. This is based on the modifications being limited to AHU/coil relocation work only because the compressors and associated controls and piping have been removed as part of the NH_3 plant integration. The Council's plans in relation to opening up the accesss to the central garden are as yet not developed and modification cost reductions can therefore not be detailed further.

Air conditioning systems employing ammonia as the primary refrigerant are in many cases technically and commercially viable in both new and existing commercial buildings. Commercial viability of NH_3 is assisted significantly by the introduction of the HFC Levy of $23.00/ton of CO_2e taking effect 1 July 2012. Individual circumstances such as engine room location, existing system concept and peripheral issues can impact on the decision process. Careful evaluation of each individual situation considering all these relevant factors is necessary to ensure a successful installation and integration with minimum disruption.

A potentially significant barrier for successful transition from chemical to natural refrigerants within the built environment in Australia are the perceptions associated with natural refrigerants in terms of toxicity, flammability and high operating pressures in the case of CO_2. Where many local Government jurisdictions often display resistance towards natural refrigerants due to various misconceptions relating to risk, Logan City Council embraced the natural refrigerant alternative with significant foresight and a positive attitude towards risk management.

Refrigerant ammonia has been in successful use worldwide for more than 130 years. Ammonia has an admirable safety record in refrigeration applications with statistically less than 2 fatalities per 1,000,000,000 inhabitants per year [4]. This safety record is a result of the high safety and installation standards that have evolved as a result of many years of international cooperation among natural refrigerant practitioners.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

(a) Journal Articles:

1. Spolc, D.J. "A Local Government Journey To A Cheaper, Greener Air Conditioning Future". AIRAH Refrigeration 2012 Conference, 24 July 2012.

2. Brodribb, P. "Refrigerant Levy Panel 'Working Bank' What are The Options?" ARBS 2012 Seminar Presentation.

3. Jensen, S.S. "Life After HFC's – Opportunity or Treat?". AIRAH 90th Anniversary Conference. Sydney, November 2010.

4. Lindborg, A. "Ammonia Safety". IIAR Exhibition and Conference, Dallas, Texas, March 23-25, 2009.