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TITLE

EUTECTIC (PCM) BASED HEAT REJECTION THERMAL ENERGY STORAGE SYSTEMS

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Synopsis

A Thermal Energy Storage (TES) may be considered as a useful tool to reduce the amount of refrigeration machinery by means of spreading day time loads over 24 a hour period. Hence, any type of TES systems can be considered as useful tool to reduce the overall environmental impact for a given cooling application.

Water / Ice TES has the advantage of universal availability and low cost. However, a conventional ice TES system for air conditioning application requires low temperature glycol chillers which operate with lower evaporation temperature during the ice build mode.

The night time ice chiller inefficiency a conventional ice storage system can be overcome by utilising the latent heat capacity of various “ Positive Temperature Eutectic” solutions instead of minus circulation temperatures. Positive Eutectic Thermal Energy Storage *“PETES”* not only enables the designer to utilise existing chiller technologies including absorption chillers, but also this technique may enable the charging process to take place by means of free cooling, i.e. without running the chillers.

Furthermore, PETES opens new opportunities to explore heat rejection TES applications, effectively controlling the condensing temperature of a cycle which offers efficiency improvements comparable to low temperature (ice) TES concepts. The main advantage of such a system is the possibility of charging TES without running the chillers and therefore this new TES system offers unmatched overall system efficiency.

This paper is extended to investigate alternative and new TES systems in the form of Positive Eutectic Solutions. Practical application guidance as well as numerical installation, running and energy studies are also incorporated as part of this paper.

1.0 - BACKGROUND

Thermal Energy Storage (TES) reduces the amount of refrigeration machinery by means of spreading the day time load over either night time as in the case of Full Storage TES systems or alternatively over 24 hours period in the case of Partial Storage TES systems. Hence, any type of TES systems can be considered as a useful tool to reduce the overall environmental impact for a given comfort cooling application.

A conventional Ice TES has the advantage of universal availability and low cost. However, a conventional ice TES system for air conditioning application requires low temperature chillers and therefore standard water chillers must be selected to operate with a lower evaporation temperature.

The disadvantages of a conventional ice storage system can be overcome by utilising the latent heat capacity of various " Positive Temperature Eutectic" mixtures without the need for minus circulation temperatures. Positive Eutectic Thermal Energy Storage *"PETES"* not only enables the designer to utilise alternate chiller technologies including absorption chillers, but also this technique enables charging process to take place possibly by means of free cooling, i.e. without running the chillers.

2.0 - THERMAL ENERGY STORAGE:

Thermal Energy Storage is the temporary storage of high or low temperature energy for later use. It bridges the gap between energy requirement and energy use. A thermal storage application may involve a 24 hour or alternatively a weekly or seasonal storage cycle depending on the system design requirements. Whilst the output is always thermal, the input energy may be either thermal or electrical.

In full storage systems, the entire load for the design day is generated off peak and stored for use during the following peak period. In partial storage systems, only a portion of the daily load is generated during the previous off peak period and put into storage. During the peak period, the load is satisfied by a simultaneous balancing operation of the installed machinery and stored energy in order to satisfy the overall daily design duty.

2.1 Current TES Technologies :

For HVAC and refrigeration application purposes, water and phase change materials (PCM) constitute the principal storage media. Water has the advantage of universal availability, low cost and transport ability through other system components. However, a conventional water based TES systems for air conditioning applications require either low temperature glycol chillers which operate with lower evaporation temperatures or large volumes of chilled water storage.

Ice production techniques can be divided into two main groups namely ***Dynamic*** and ***Static*** systems (Ure.Z,1997) as shown in Table 2.1. The produced ice can be used either ***directly*** to chill products such as fish, vegetables, meat, poultry etc. or ***indirectly*** as a secondary coolant for latent heat cooling effect for process cooling such as ice storage, TES systems for air conditioning and process cooling as a secondary cooling medium.

STATIC ICE PRODUCTION	DYNAMIC ICE PRODUCTION
1 - Ice Builders **2 - Ice Banks** **3 - Encapsulated Ice Modules** **a) Balls** **b) Flat Containers**	**1 - Plate Harvester** **2 - Tube Harvester** **3 - Flake Ice Machines** **4 - Binary Ice Machines**

Table 2.1 - Current Ice Production Technologies

2.2 - Positive Eutectic Thermal Energy Storage *(PETES)* Systems :

Positive Eutectic Thermal Energy Storage ***(PETES)*** not only enables the designer to utilise existing chiller technology without the need for minus circulation temperatures, but also may enable charging by means of free cooling, i.e. without running the chillers (Ure,Z., 1997)

Although the term "Eutectic" is widely used to describe the materials we are interested in, a better description would be "Phase Change Materials" ("PCMs"). A true eutectic is a mixture of two or more chemicals which, when mixed in a particular ratio, have a freezing/melting point which is lower than the corresponding freezing points of the component chemicals. During the freezing/melting process (phase change) the composition of the solid and liquid phases are identical.

Unfortunately, very few of the PCMs are true Eutectics and so many have to be modified to obtain a material suitable for long term use. PCMs can be broadly grouped into two categories; ***"Organic Compounds"*** (such as polyethylene glycols) and ***"Salt-based Products"*** (such as Glauber's salt). Each group of PCMs comes with its advantages and disadvantages (Ure.Z, 1998) some of which are listed in Table 2.2.

	Advantages	**Disadvantages**
ORGANICS	* Simple to use * Non-corrosive * No supercooling * No nucleating agent	* Generally more expensive * Lower latent heat/density * Often give quite broad melting range * Can be combustible
SALT-BASED	* Generally cheap * Good latent heat/density * Well defined phase change temperature * Non-flammable	* Need careful preparation * Need additives to stabilise for long term use * Prone to supercooling * Can be corrosive to some metals

Table 2.2 - Characteristics of PCMs

Much work has been done over the years using one particular PCM, namely Glauber's salt or sodium sulphate decahydrate. It normally freezes at 32.5 ºC, (90.5 °F) which has made it ideal for use in solar heating installations (Lane,G.A.,1993), but by the addition of other salts it is possible to depress the phase transition temperature to around 8.3 ºC (47 °F) and this facility has made Glauber's salt an attractive proposition for example with air conditioning applications (Ames, D.A., 1990).
However, Glauber's salt melts incongruously and the salt tends to separate into a saturated solution with insoluble anhydrous sodium sulphate crystals. Since these crystals are more

dense than the saturated solution they tend to settle out of solution due to gravity. When the PCM is next frozen these crystals are unable to recombine with the saturated solution, resulting in a loss in TES capacity of the system (ITSAC, 1989). This occurs during each freeze/melt cycle, and if unchecked leads to a gradual but continual loss of performance.

A wide variety of thickening agents have been applied in the past (Telkes,M.,1974). The most widely used material was a clay-like substance but the recent work has concentrated on using other thickening agents, in particular synthetic polymer gels. A number of suitable polymers have been identified which can function satisfactorily in the harsh environment of the PCM mixture (Ure, Z.,1998). New ways of producing stable, efficient, and easily applicable PCMs are being developed which will help raise the profile of PCM thermal energy storage.

Following extensive research, the authors has identified a number of satisfactory PCMs which melt and freeze between + 4 ° C (39.2 °F) and + 117 ° C (242.6 °F) and therefore suit the majority of the air conditioning and refrigeration applications. A number of these PETES solutions are incorporated in Table 2.3.

PETES Solution	Phase Change Temp. (°C/°F)		Density (kg/m^3) / (lb/ft^3)		Heat of Fusion (kJ/kg) / (Btu/lb)		Latent Heat (MJ/m^3) /(Btu/ft3)	
A4	**4**	39.2	**766**	47.8	**227**	97.6	**174**	4665
E8	**8**	46.4	**1473**	91.9	**95**	40.8	**141**	3749
A8	**8**	46.4	**773**	48.2	**220**	94.6	**170**	4559
E10	**10**	50	**1470**	91.7	**215**	92.4	**315**	8473
E13	**13**	23.4	**1519**	94.8	**213**	91.6	**324**	8683
E15	**15**	59	**1780**	111.1	**140**	60.2	**249**	6688
A15	**15**	59	**780**	48.6	**231**	99.3	**180**	4825
E18	**18**	64.4	**1569**	97.9	**212**	91.1	**330**	8918
E21	**21**	68.9	**1615**	100.8	**191**	82.1	**307**	8275
E24	**24**	75.2	**1704**	106.3	**167**	71.8	**285**	7632
E27	**27**	80.6	**1562**	97.5	**191**	82.1	**298**	8004
A28	**28**	82.4	**789**	49.2	**245**	105.3	**193**	5180
E30	**30**	86	**1374**	85.7	**200**	86.1	**275**	7378
E32	**32**	89.6	**1460**	91.1	**251**	107.9	**335**	9829
E34	**34**	93.2	**1585**	98.9	**265**	113.9	**379**	11264
E58	**58**	136.4	**1280**	79.9	**226**	97.2	**289**	7766
E89	**89**	192.2	**1550**	96.7	**163**	70.1	**253**	6778
E117	**117**	242.6	**1450**	90.5	**169**	72.6	**245**	6570

A - Alkine / Aliphatic Based Solution E- Eutectic Based Solution

Table 2.3 - PETES Solution Range

A typical PCM freezing and melting curve can be seen in Figure 2.3 for 10 °C (50 °F) solution. Other PETES solutions also indicate a similar pattern of freezing and melting curves within their intended temperature ranges.

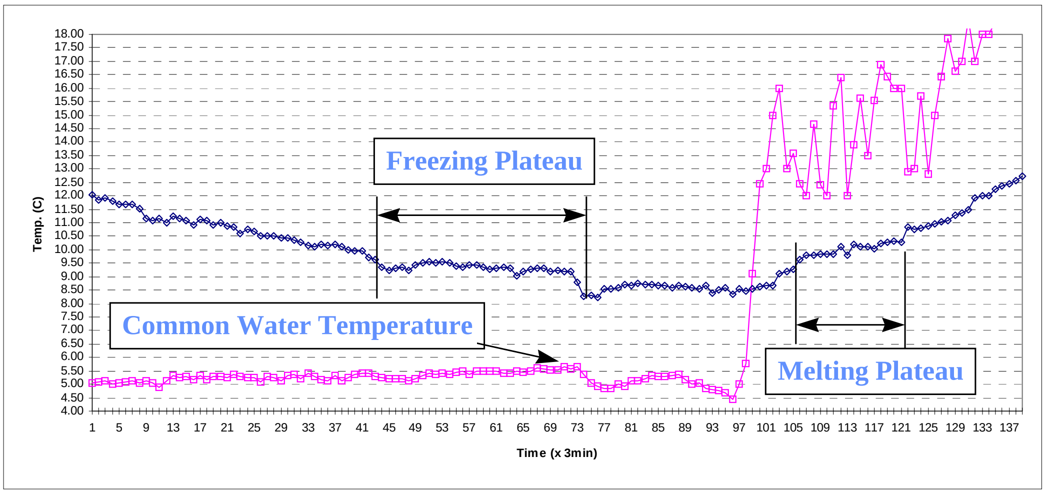

Figure 2.3 - Freezing and Melting Curve for 10 °C (50 °F) Eutectic Solution.

A small scale 18 kWh (5.12 TR-h) site installation was completed in September 1997. So far neither early laboratory samples produced late 1995 (which were subject to accelerated daily charge / discharge cycle simulations) nor the above site have shown loss of performance or segregation.

3.0 - PETES AND ASSOCIATED ENERGY EFFICIENCY:

Irrespective of the type of refrigerant used it is vital to improve energy efficiency for any given refrigeration system in order to achieve an environmentally friendly design. Every compression refrigeration cycle operates between a discharge and suction pressure envelope which dictates the cycle shown in Figure 3.1.

The efficiency of the cycle can be improved by utilising different types of refrigerant, compressor, condensing, evaporating and expansion devices, but the cardinal rule of energy efficiency dictates that ***"lower condensing pressures and higher evaporation temperatures lead to less compressor energy consumption for a given refrigeration duty",*** therefore designers should aim to achieve the above requirement within the design limits for a given system.

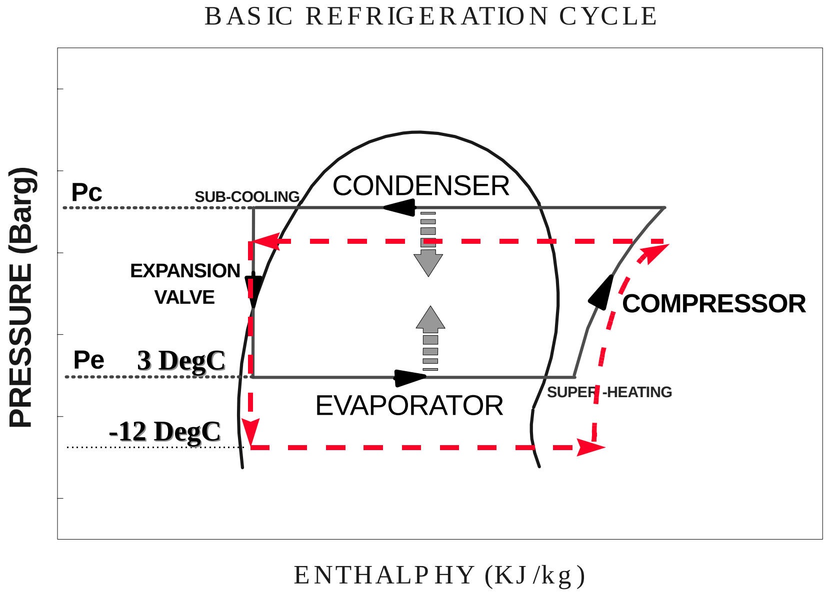

Figure 3.1 - Cardinal Rule for the Refrigeration Energy Efficiency

The benefits gained by lower ambient conditions are somewhat compromised by lowering evaporation temperature (as illustrated in Figure 3.1 dotted lines indicate ice build periods for a conventional ice TES system). Hence, PETES Thermal Energy Storage systems offers a higher overall COP for the system by means of maintaining conventional chilled water temperatures during charging periods.

The above concept benefit is illustrated in Figure 3.2 showing a typical Air Cooled Chiller operation for normal day, night ice chiller and night PETES charging operation against various ambient air temperatures.

It can be clearly seen that a PETES concept offers a significant overall performance improvement in comparison with a conventional ice TES application and the same concept can be applied for water cooled chillers, heat driven chillers such as Li-Br Absorption chillers for both new and retrofit applications.

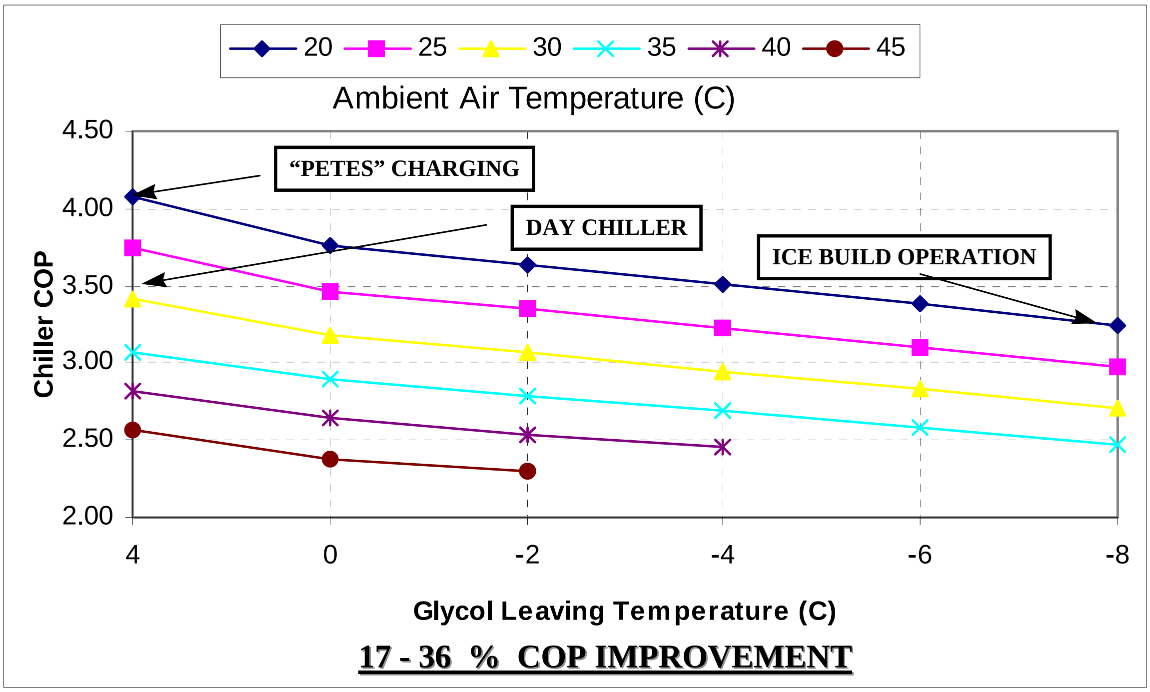

Figure 3.2 - Air Cooled Chiller Chiller / Ice Chiller Operation Comparison

Furthermore, PETES opens new opportunities to explore heat rejection TES applications, effectively controlling the condensing temperature of a cycle which offers efficiency improvements comparable to low temperature (ice) TES concepts. The main advantage of such a system is the possibility of charging TES without running the chillers and therefore this new TES system offers unmatched overall system efficiency.

If we use Eutectic Solutions which freeze and melt between the day peak and night low ambient temperatures the system can be charged without running chiller(s) simply by operating the heat rejection circuit in order to utilise free air cooling options.

Primarily, the system TES can be charged without running chiller and therefore considerable energy saving for the TES. Secondly, the stored thermal energy controls and reduces condensing temperatures during the peak ambient periods, hence, further energy savings during the day operation periods.

A typical example of this concept is illustrated in Figure 3.3 for conventional Dry Cooler and Cooling Tower installations with or without a PETES. Traditional heat rejection circuits operate between 25 °C (77 °F) and 45 °C (113 °F) water circulation temperatures during the high ambient periods and the night time temperatures are generally at least 10 - 15 °C (18 - 27 °F) lower than the day peak dry bulb conditions. These temperatures variations differs from one country / region to another nevertheless day versus night time ambient variations occur universally.

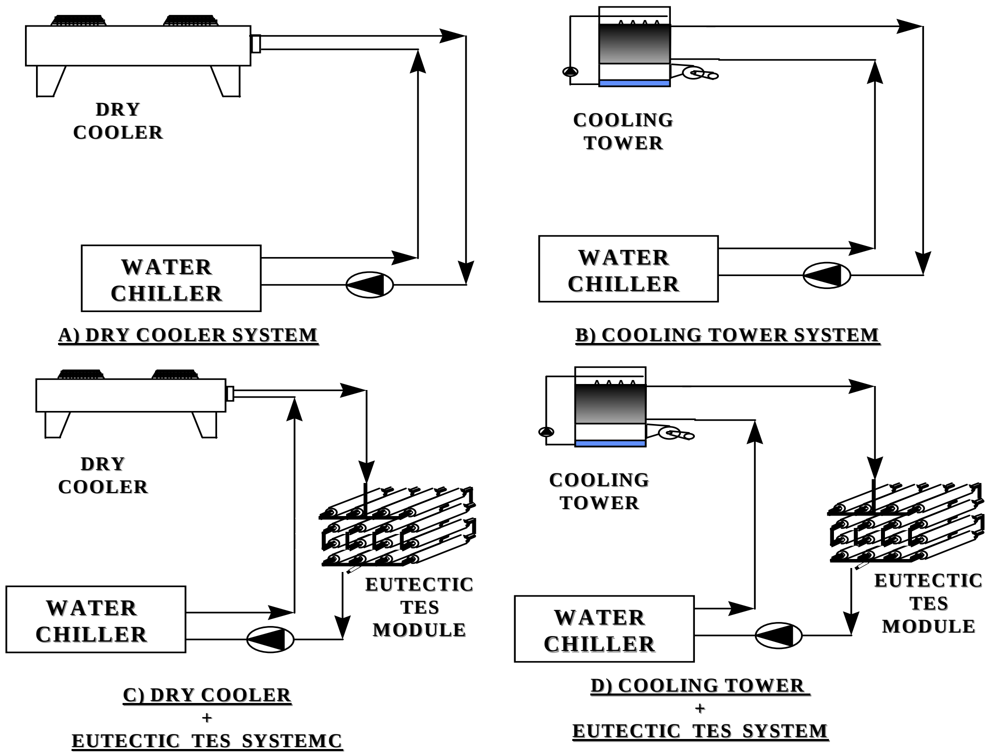

Figure 3.3 - Heat Rejection TES Application

Relevant energy consumption studies are carried out for an identical 374 kW (106.25 RT) water cooled chiller for the above applications (Table 3.1) in order to evaluate the selected water chiller operation for various ambient operations.

Refrigerant		R134a					
Condensing (C)	(F)	Capacity (kW)	(TR)	Power (kW)	COP	THR (kW)	THR (MBTU/h)
30	86	374	106	78.1	4.78	452	1542
35	95	374	106	89.3	4.19	463	1581
40	104	374	106	104.2	3.59	478	1631
45	113	374	106	126.1	2.97	500	1706
50	122	374	106	143.6	2.60	517	1766

Table 3.1 - Water Cooled Chiller Operation

Based on the operational data in Table 3.1 a full energy consumption study is developed utilising ambient segment concept (BRA, 1996) and the installation cost studies for the system covered in Figure 3.3 is summarised in Table 3.2.

POSITIVE EUTECTIC TES HEAT REJECTION APPLICATION								
AMBIENT & SEGMENT DATA								
SEGMENT No:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**TOTAL**
Ambient Temperature (C)	32	27	22	17	12	7	2	
Ambient Temperature (F)	89.6	80.6	71.6	62.6	53.6	44.6	35.6	
Running Hours	13	145	692	2152	2863	2106	789	**8760**
A) DRY COOLER SYSTEM								**kWh**
Chiller	1866	18283	72133	192229	223731	0	0	**508243**
Heat Rejection	414	4612	22013	68455	91072	0	0	**278656**
GRAD TOTAL (kWh)								**786898**
B) COOLING TOWER SYSTEM								**kWh**
Chiller	1355	12952	54077	142944	167798	0	0	**379127**
Heat Rejection	371	4135	19734	61370	81646	0	0	**249814**
GRAD TOTAL (kWh)								**628941**
C) PETES + DRY COOLER SYSTEM								**kWh**
Chiller	933	9141	36067	96115	111866	0	0	**254121**
Heat Rejection	457	5098	24331	75664	100663	0	0	**154001**
GRAD TOTAL (kWh)								**408122**
D) PETES + COOLING TOWER SYSTEM								**kWh**
Chiller	678	6476	27038	71472	83899	0	0	**189563**
Heat Rejection	309	3449	16461	51191	68104	0	0	**139514**
GRAD TOTAL (kWh)								**329078**

Table 3.2 - A Typical PETES Heat Rejection Energy Consumption Study

POSITIVE EUTECTIC TES HEAT REJECTION APPLICATION												
System Type	**Dry Cooler System**			**Cooling Tower System**			**PETES + Dry Cooler**			**PETES + Cooling Tower**		
	Per Unit	**Qty**	**TOTAL**	**Per Unit**	**Qty**	**TOTAL**	**Per Unit**	**Qty**	**TOTAL**	**Per Unit**	**Qty**	**TOTAL**
HEAT REJECTION SYSTEM												
Fan Power (kW)	2.33	4	9.30	6.69	2	13.39	2.33	2	4.65	6.69	1	6.69
Spray Pump (kW)	0	0	0.00	1.1	2	2.20	0.00	0.00	0.00	1.10	1.00	2.20
Circulation Pump (kW)	22.51	1	22.51	12.93	1	12.93	12.93	1.00	12.93	3.00	1.00	3.00
SYSTEM TOTAL (kW)			**31.81**			**28.52**			**17.58**			**11.89**
REFRIGERATION SYSTEM												
A/C Service			50.43			41.70			35.73			31.26
SYSTEM TOTAL (kW)			**50.43**			**41.70**			**35.73**			**31.26**
Annual System Total (kWh)			**786898**			**628941**			**408122**			**329078**
Ratio (%)						**79.93**			**51.86**			**41.82**
Average Day Unit Cost	0.05 p/kWh											
Average Night Unit Cost	).023 p/kWh											
Availability Charges	£1.1 / kVa		**666**			**550**			**472**			**413**
Electricity Night Cost (£)									**1033**			**699**
Electricity Day Cost (£)			**39345**			**31447**			**20406**			**16454**
TOTAL ANNUAL RUNNING COST (£/pa)			**40011**			**31997**			**21911**			**17565**
Running Cost Saving (£/pa)						**8013**			**18100**			**22445**
Ratio (%)						**79.97**			**54.76**			**43.90**
Installed System Cost Study												
			(£)			**(£)**			**(£)**			**(£)**
TES							55000	1	55000	55000	1	55000
Dry Cooler/Cooling Tower	18805	4	75220	20032	4	80128	18805	2	37610	20032	1	20032
Pump	2500	1	2500	2000	1	2000	2500	1	2500	2000	1	2000
Pipework	107.93	500	53965	80.37	500	40185	80.37	500	40185	80.37	500	40185
INSTALLED TOTAL COST (£)			**131685**			**122313**			**135295**			**117217**
Ratio (%)						**93**			**103**			**89**

Table 3.3 - A Typical PETES Heat Rejection Power, Running and Installation Cost Study

Results shown in Tables 3.2 and 3.3 results confirm that the proposed heat rejection control PETES concept offers very attractive economical and environmental benefits for both Dry Cooler and Cooling Tower heat rejection applications. These figures also indicate that the proposed heat rejection control concept can be applied economically for new installations within the same cost restrictions as conventional systems and offer significant running cost savings.

Furthermore, the above study also indicates that a PETES heat rejection concept offers attractive retrofit applications either for increasing system capacity, without adding any additional chillers, or alternatively reducing the energy consumption for an existing system. Either ways the pay back remains within the commercially acceptable level of 2-3 years.

4.0 - CONCLUSION:

Modern society's reliance on refrigeration and air conditioning indicates that refrigeration and the associated environmental issues will be with us for a considerable time and therefore one has to utilise existing and available alternative technologies with minimum usage of energy.

A PETES concept not only provides the end user with an Environmentally Friendly and economical design but also offers the following additional benefits :

- **Reduced Equipment Size**
- **Capital Cost Saving**
- **Energy Cost Saving**
- **Energy Saving**
- **Improved System Operation**
- **Flexibility for the Future Capacities**

PETES operating temperatures remains within conventional chilled water temperature range and therefore it can be easily applied for retrofit application for existing sites including Li-Br absorption chillers with minimal modifications.

PETES concept offers new horizon for heat rejection TES applications which offer comparable energy savings with conventional ice TES systems during day operation. However, this new concept enables TES charging process to take place utilising night time low ambient temperatures instead of running the chiller(s) and therefore a PETES Heat Rejection Control Concept offers unmatched overall system efficiency and economically attractive new and retrofit applications.

Existing technology is moving towards between containment of refrigerants in order to reduce Direct Global Warming Impact, but the CO_2 emission related to energy usage will be with us as long as current electrically driven refrigeration technology remains.

Therefore, the task for designers is to explore all the available technologies towards achieving improved efficiency regardless of which refrigerant is used, and apply where and when possible diversification technologies in order to minimise the overall CO_2 emission related to energy usage. A carefully balanced PETES may be the answer for some of the cooling applications for an Environmentally Friendly and Economical alternative.

5.0- NOMENCLATURE

PES	-	Positive Eutectic Solutions.
PETES	-	Positive Eutectic TES.
TES	-	Thermal Energy Storage.
COP	-	Co-Efficiency of Performance.
PCM	-	Phase Change Materials.
HVAC	-	Heating Ventilation Air Conditioning.
THR	-	Total Heat Rejection.
R134a	-	HFC Based Refrigerant.

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