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TITLE

POSITIVE TEMPERATURE EUTECTIC (PCM) THERMAL ENERGY STORAGE SYSTEMS

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Synopsis;

Thermal Energy Storage (TES) may be considered as a useful tool to reduce the number of refrigeration machinery by means of spreading the daytime load over 24 hours period. Hence, any type of TES systems can be consider as useful tool to reduce the overall environmental impact for a given cooling application.

Water / Ice TES has the advantage of universal availability, low cost and transport ability through other system components. However, a conventional water based TES system for air conditioning application requires low temperature chillers and therefore standard water chillers must be replaced with low temperature glycol chillers which operate with a lower evaporation temperature.

The disadvantages of a conventional HVAC chiller and ice (water ice) storage system can be overcome by utilising the latent heat capacity of various "Eutectic" mixtures without the need for minus circulation temperatures. Plus temperature thermal energy storage PlusICE not only enables the designer to utilise existing chiller technology, but also this technique enables charging process to take place possibly by means of free cooling, i.e. without running the chillers.

This paper is extended to investigate the alternative TES systems in the form of Eutectic PlusICE Solutions. The results of performance tests for various temperature ranges as well as the practical application guidance are also incorporated as part of this paper.

1.0 – BACKGROUND

Energy usage, economical and environmental issues are becoming the focal points for both end-users and the public at large. Current trends towards privatisation and an open market approach for utility companies has created a new kind of energy market whereby the period of energy usage and the type of energy used is becoming the main criteria for price structuring (Beggs C., Ure Z ., CIBSE / ASHRAE Joint National Conference, Part II, Harrogate, Sep. 1996, UK) rather than overall energy consumption.
Hence, current building services must be designed to provide sufficient flexibility for load shifting and energy usage control in order to achieve the most economical operation. A Thermal Energy Storage technique whereby **" Storing High or Low Temperature energy for later use in order to bridge the time gap between energy availability and energy use** " can be considered as a useful tool to achieve this aim.

Unfortunately **HVAC & Refrigeration TES** applications utilise water ice which can only be produced with low temperature chillers. As a result, the benefits of night time low ambient temperature, existing water chillers and possibly free ambient cooling options cannot be fully utilised. If we can offer designers ICE which freezes and melts above 0°C (32 °F) this product will open new horizons for environmentally friendly and economical systems for both New and Retrofit type process cooling / heating load shifting applications.

This paper investigates Positive Temperature Eutectic Solutions for long term TES usage to achieve the above aim. Relevant application guidance along with typical application examples are also incorporated within this paper.

2.0 - THERMAL ENERGY STORAGE:

Thermal Energy Storage bridges the time 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 design 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.

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 system for air conditioning applications require low temperature chillers and therefore standard water chillers must be replaced with low temperature glycol chillers which operate at lower evaporation temperatures (Ure Z ., CIBSE / ASHRAE Conference, Harrogate, Sep. 1996, UK.) Ice production techniques can be divided into two main groups namely ***Dynamic*** and ***Static*** systems (Ure Z., “Alternative Technology”, Page 20-22, October 1996, RAC Journal)

3.0 - POSITIVE TEMPERATURE EUTECTIC TES SYSTEMS :

Positive Temperature Eutectic Solutions are mixtures of two or more chemicals which, when mixed in a particular ratio, have a freezing / melting point above water freezing temperature of 0°C (32 °F) and they offer a thermal energy storage facility between **+4 °C (39 °F) and +117 °C (242 °F).** Eutectics are well-known and in fact early applications date back to the late 18th century however the separation and the life expectancy of these mixtures were unpredictable and therefore their wide spread usage was limited.
The disadvantages of a conventional HVAC chiller and ice (water ice) storage system can be overcome by utilising the latent heat capacity of various “Eutectic” mixtures without the need for minus circulation temperatures. Positive temperature thermal energy storage ***“Plus*ICE”** not only enables the designer to utilise existing chiller technology but also enables charging by means of free cooling (Burton G, Ure Z , CIBSE National Conference, Volume II, Alexandra Palace, Oct. 1997, UK), i.e. without running the chillers.
Although the term “Eutectic” is widely used to describe the materials we are interested in, a better description would be “Phase Change Materials” (“PCMs”). Unfortunately, very few of the documented PCMs (a number of

which are listed in Table 3.1) (ASHRAE Handbook, “HVAC Systems and Applications “, Issue : 1987, Section 46) are true Eutectics and so many have to be modified to obtain a material suitable for long term use.

Material	**Melt Point**		**Heat of Fusion**		**Latent Heat**	
	(ºC)	**(ºF)**	**kJ/kg**	**Btu/Lb**	**MJ/m3**	**Btu/Lb**
$MgCl_2.6H_2O$	117	243	169	73	242	6,499
$Mg(NO_3)_2.6H_2O$	89	192	163	70	252	6,768
$CH_3COONa.3H_2O$	58	136	226	97	287	7,708
$MgCl_2.6H_2O$/ $Mg(NO_3)_2.6H_2O$	58	136	132	57	201	6,499
$Na_2HPO_4.12H_2O$	34	93	265	114	379	10,179
$Na_2SO_4.10H_2O$	32	90	251	108	335	8,997
$Na_2CO_3.10H_2O$	32	90	233	100	340	9,131
Waxes	28 to 4	82 to 39	220 to 245	94 to 105	170 to 195	4,564 to 5,237
Polyethylene glycols	28 to -15	82 to -9	146 to 155	62 to 66	165 to 175	4,431 to 4,699
$CaCl_2.6H_2O$	27	81	191	82	298	8,003
Glauber’s salt + additives	24 to 4	75 to 39	wide range	wide range	wide range	wide range
$CaCl_2.6H_2O$/ $CaBr_2.6H_2O$	15	59	140	60	249	6,687
Water	0	32	335	144	335	8,997
Range of water/salt Eutectics	0 to -64	32 to -83	Wider range	Wider range	wide range	wide range

Table 3.1 - Range of commonly used PCMs

PCMs can be broadly grouped into two categories; ***”Organic Compounds“*** (such as polyethylene glycol) and ***“Salt-based Products”*** (such as Glauber’s salt). Each group of PCMs comes with advantages and disadvantages some of which are listed in Table 3.2 (Burton G, Ure Z , CIBSE National Conference, Volume II, Alexandra Palace, Oct. 1997, UK).

	Advantages	**Disadvantages**
ORGANIC	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 3.2 - Characteristics of PCMs

The fundamental requirement for a Modified Eutectic Solution can be classified in three categories, namely stable solution (no separation or degrading), minimum supercooling / heating and finally close freezing and melting temperatures as illustrated in Figure 3.1. There are three fundamental additives commonly used to modify Eutectic solutions covered in Table 3.1 for long term use. The first additive is ***Nucleating Agent*** which encourages Crystal formation and therefore minimises super cooling and the second additive is ***Freeze Depressant*** to achieve a lower phase change temperature.

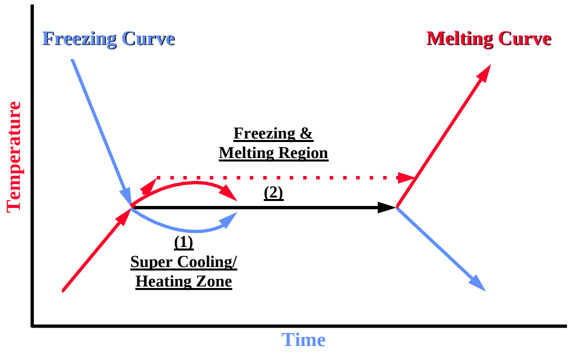


Figure 3.1 - Eutectic PCM Freezing / Melting Curve

The third and final additive is the ***Gelling/ Thickening Agent*** in order to overcome separation and degrading problems. Once the above components have been carefully applied, a satisfactory Eutectic Solution can be produced from the physical and thermodynamic point of views. However, majority of suitable PCM solutions for HVAC and refrigeration systems are corrosive to commonly used pipe and line components and therefore a suitable encapsulation techniques must be applied to overcome this problem while providing the best thermal performance. Various encapsulation techniques such as tube, flat container or alternatively ball concepts have been developed whereby the PCM solution is encapsulated in plastic and / or metal shell as illustrated in Figure 3.2 (Burton G, Ure Z , CIBSE National Conference, Volume II, Alexandra Palace, Oct. 1997, UK)

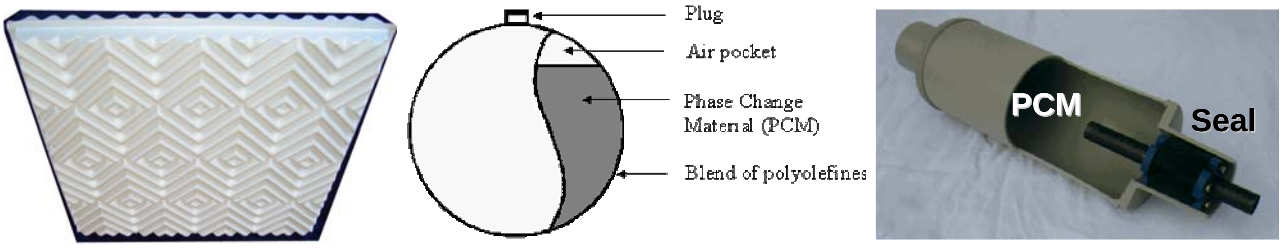


Figure 3.2 - *Plus*ICE PCM Concepts

The heat transfer between the surrounding media, which flows around or inside the unit and the surrounding PCM solutions, takes place from the outer or inner or the combination of both surfaces of the encapsulated PCM units. These techniques are generally eliminates the contamination risk and offers an efficient, cost effective, practical and flexible TES applications.

4.0 - TES AND ASSOCIATED ENERGY EFFICIENCY:

Irrespective of the type of refrigerant used, it is vital to improve the energy efficiency for any given refrigeration system in order to achieve an environmentally friendly design Every compression refrigeration cycle operates between the discharge and suction pressure envelope, which dictates the cycle shown in Figure 4.1.

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 energy consumption for a given refrigeration duty"*** therefore designers should aim to achieve the above requirement within the design limits for a given system.

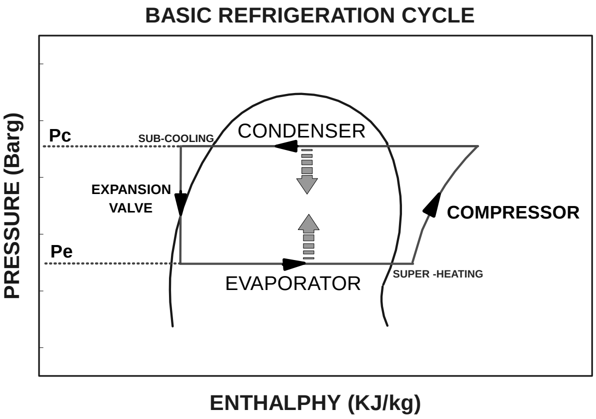


Figure 4.1- Cardinal Rule for the Refrigeration Energy Efficiency

If a Positive Temperature Eutectic Thermal Energy Storage system is incorporated as part of the cycle, it offers the following energy efficiency features;

* Higher evaporation temperature during TES charging leads to less power consumption.
* Lower condensing pressure reduces the compressor power consumption.
* Free sub-cooling TES increases the cooling capacity and the overall COP.
* Superheat control TES improves the compressor operation.
* Lower night-time ambient conditions may offer free TES charging.

5.0 - PlusICE APPLICATIONS ;

Positive Temperature Eutectic Solutions between **+4 °C (39 °F)** and **+117 °C (242 °F)** can not only be charged using conventional water chillers and the temperature range also offers the following additional TES applications for a cost effective energy management concept for both New and Retrofit type process cooling / heating load shifting applications.;

*** Absorption & Co-Generation.**
*** Cooling Tower / Dry Cooler Circuit Load Shifting.**
*** Heat Recovery / Solar Heating Systems.**
- **Free Ambient Cooling Circuit.**

The beam design shown in Figure 3.2 can be filled with any of the proposed PCM solutions in Table 3.1. The positive temperatures offered by this concept opens a revolutionary new way of thermal energy storage whereby designers can utilise conventional chilled water and refrigeration temperature ranges to charge the TES system.
Furthermore, the heat rejection side of the refrigeration cycle, free cooling and heat recovery TES concepts can also be incorporated in order to minimise the maximum demand charges and energy consumption of the system. A possible combination of the proposed beam concept for both HVAC and refrigeration side of the system is incorporated in Figure 5.1 (Burton G, Ure Z , CIBSE National Conference, Volume II, Alexandra Palace, Oct. 1997, UK).

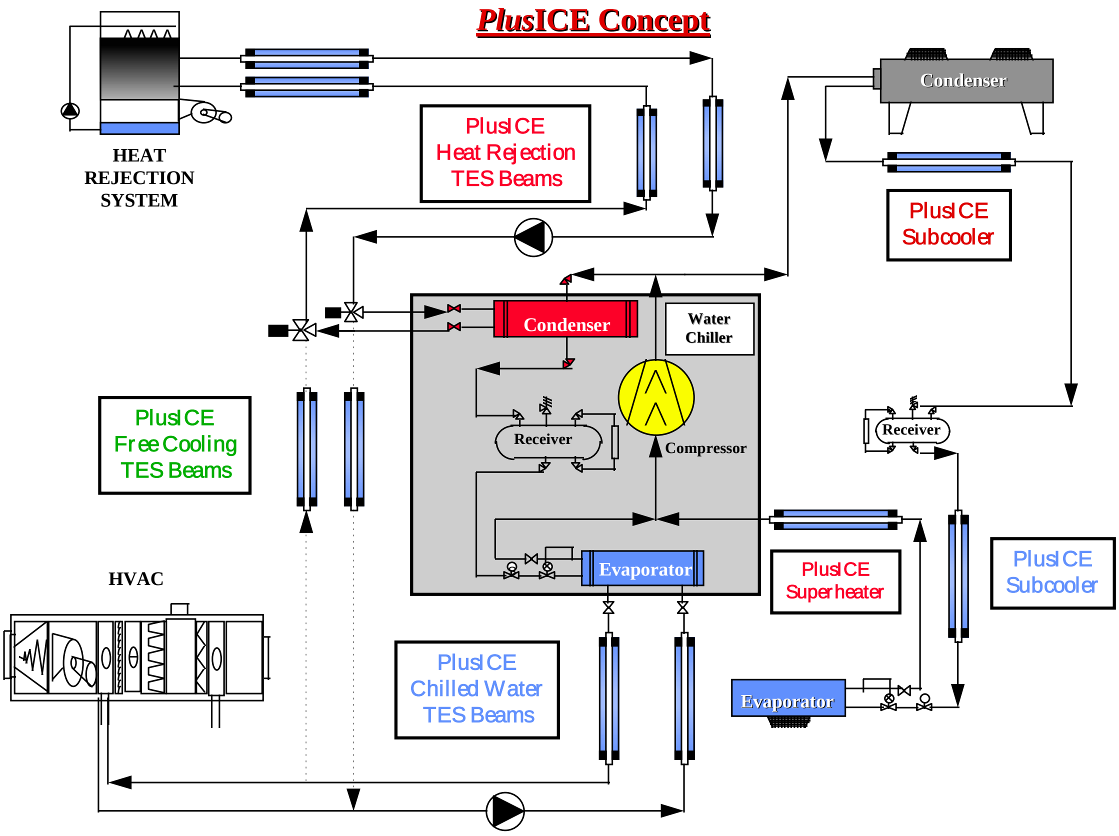


Figure 5.1 - *Plus*ICE PCM Beam Applications

A carefully balanced positive temperature thermal energy storage system enables designers to control the refrigeration envelope shown in Figure 4.1 and therefore the size of the refrigeration machinery can be reduced as a result of an optimum energy balance.

In particular, the possibility of a Free Cooling Circuit, Absorption chillers (Ames, D.A., ASHRAE Journal, April 1990, Co-Generation, Solar (Telkes, M., ASHRAE Journal, September 1974), Hot Water and Heat Recovery TES charging may result in further reduction of refrigeration machinery and unmatched cost effective TES installations for both new and retrofit applications.

The relevant positive temperature TES against a conventional low temperature chiller Ice Storage charging operations are illustrated for Air and Water Cooled chiller operations over a range of operating temperatures in Figure 5.2 and Figure 5.3 respectively.

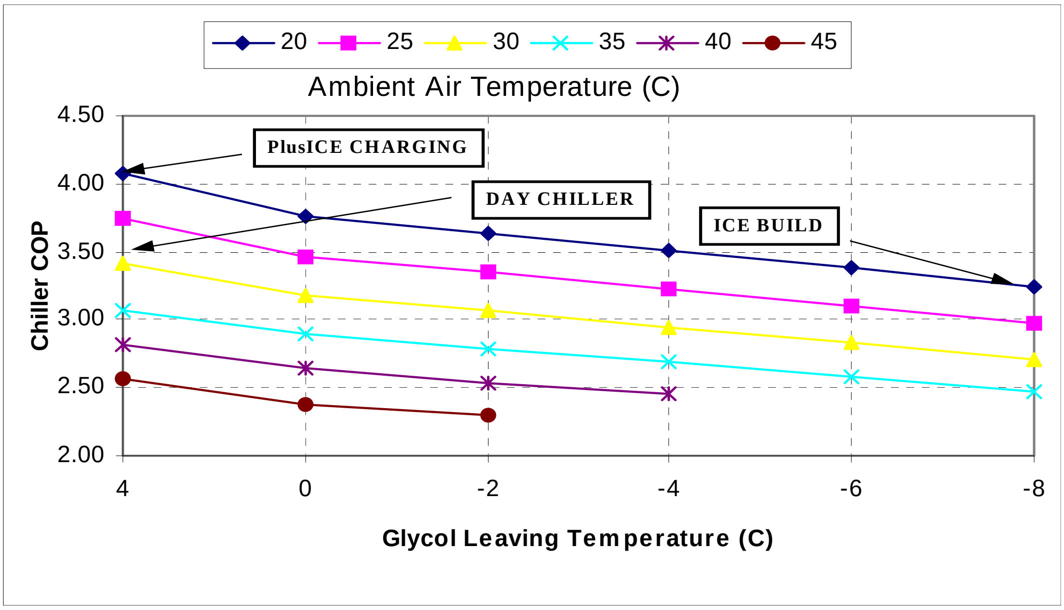


Figure 5.2 - Air Cooled Chiller PlusICE Vs Conventional Ice Charging Comparison

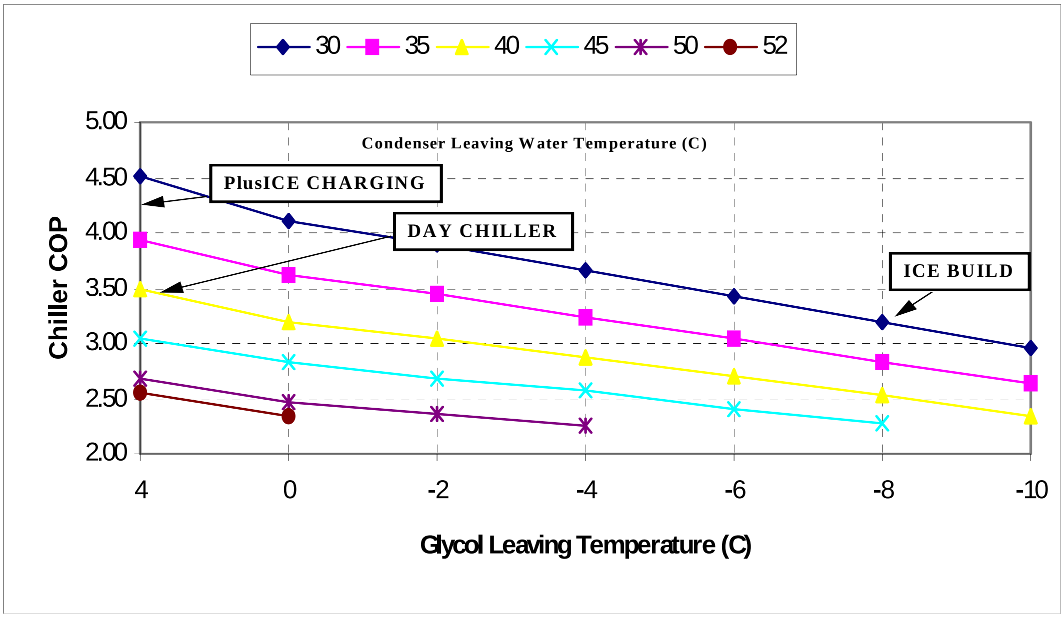


Figure 5.3 - Water Cooled Chiller PlusICE Vs Conventional Ice Charging Comparison

Low ambient temperatures coupled with higher evaporation temperatures offer a significant overall COP improvement, which is in the region of 16-46 % depending on the type of unit and location. A similar benefit can also be achieved if we apply a Positive Temperature TES for the high temperature i.e. heat rejection side of the system. A conventional design must cater for the peak ambient conditions which occur only a few days or weeks of the year ("Design Ambient Temperatures", Refrigeration Industry Board, 1985). Typical UK annual average daily wet & dry bulb temperatures as well as standard design levels are illustrated in Figure 5.4 (Met Office Data).

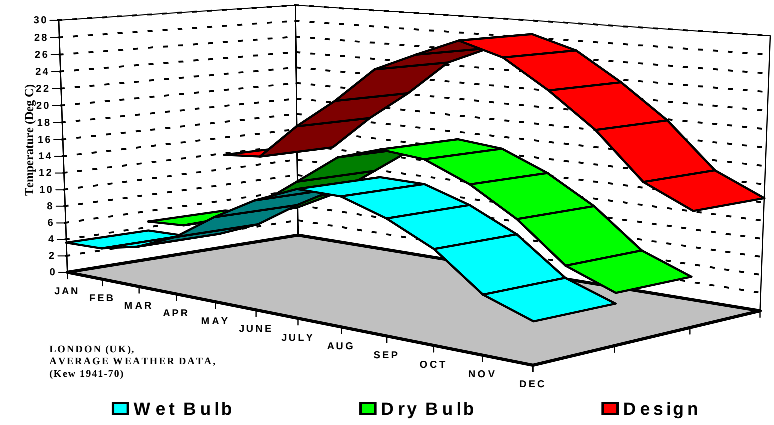
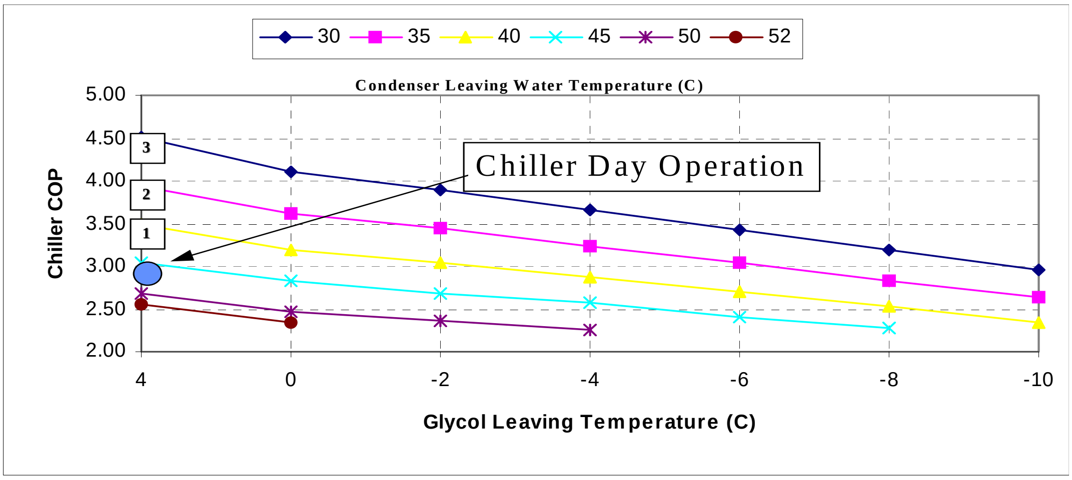


Figure 5.4 - Typical UK Annual Average Ambient Profile Vs Design Ambient

Considering the refrigeration envelope indicated in Figure 4.1, Dry Cooler / Cooling Tower circuit Heat Rejection TES can be charged by simply utilising low ambient temperatures and this free charging operation offers a significant energy and load shifting facility by controlling the Heat Rejection side of the system i.e. Condensing Pressure and effectively controlling the refrigeration machinery's energy consumption.

This principal can be applied to both Mechanical Compression and Heat Driven systems and Figure 5.5 illustrates a typical Heat Rejection TES operation for a water cooled chiller and the study indicates that the day time peak energy consumption can be reduced by as much as 33% simple by utilising the night time low ambient. In other words, the day COP improvement can be achieved without running any refrigeration machinery over night. As a result, a heat rejection TES offers unmatched efficiency, reduced running cost and an environmentally friendly concept.



COP Improvement by PlusICE TES Load Shifting

1)	5 °C REDUCTION	13 % COP IMPROVEMENT
2)	10 °C REDUCTION	23 % COP IMPROVEMENT
3)	15 °C REDUCTION	33 % COP IMPROVEMENT

Figure 5.5 - Water Cooled Chiller PlusICE Heat Rejection TES Impact on COP.

6.0 - 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 Positive Temperature Eutectic " *PlusICE* " Thermal Energy Storage not only provides the end user with an Environmentally Friendly design but also the following additional benefits can be obtained:

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

The temperature ranges offered by the proposed PCM solutions utilise conventional chilled water temperature ranges for both the charging and discharging sides of the system. Hence, they can be applied to any new or retrofit application with minimal technical and economical impacts.

Furthermore, the possibility of Free Cooling Cycle, Absorption Chillers, Co-Generation, Solar, Hot Water and Heat Recovery TES system combinations offer new horizons for designers to control the energy balance to match the load and electricity demand / consumption of the system as a whole.

The task for designers is to explore all 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 *PlusICE* Thermal Energy Storage may be the answer for some of the cooling applications for an Environmentally Friendly and Economical alternative.

7.0 - REFERENCES:

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