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Evaluation of Overall Chiller Performance Characteristics

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A water chilling machine is the most important component of a central airconditioning system. There are several types of chillers available viz reciprocating, rotary screw, centrifugal, centrifugal with VSD etc. All these chillers behave differently at varying operating conditions (cooling load and coincident cooling fluid temperatures), which are application specific. Thus, for determining the most efficient type of chiller for a particular application, the year round performance, and not just the performance at the design conditions, needs to be evaluated. The criteria as laid down by ARI - Standard 550/590 (1998) for determining the overall performance of chillers is generalized, and as a result can only predict nonapplication specific performance behavior. See **Table 1** and **Figure 1**.

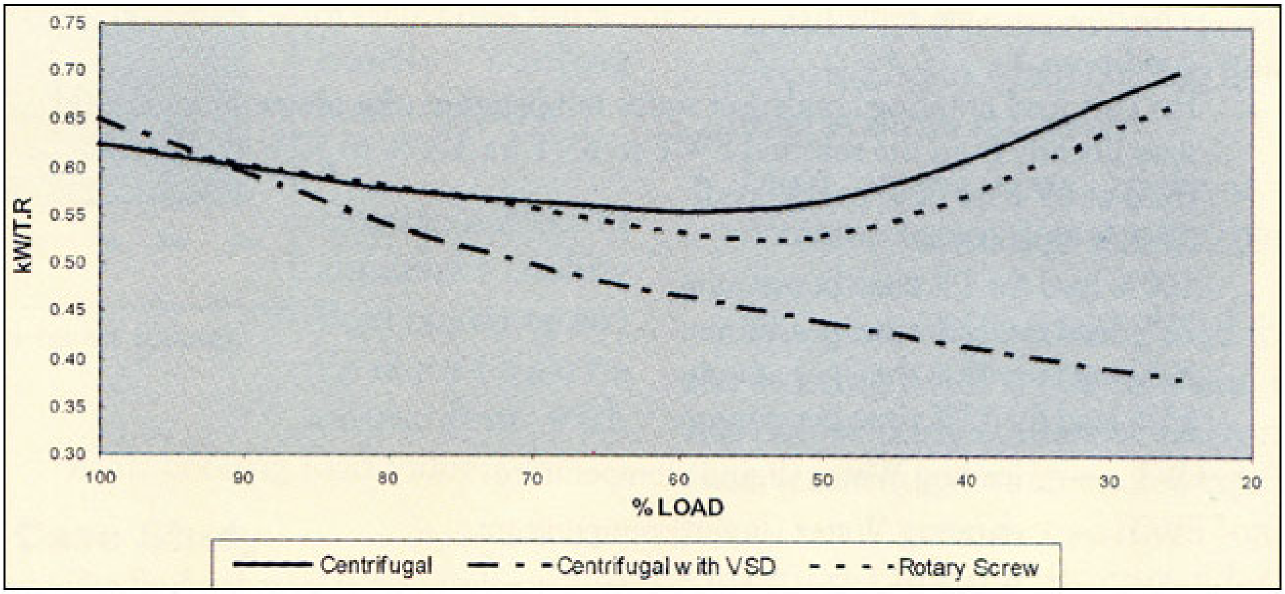

Figure 1 : Typical Part Load performances of chillers as per *ARI–Std. 550/590 (1998)*

Chiller Performance Evaluation Criteria

Most often, the flow through the condenser and evaporator of a chiller are kept constant. Thus, condenser cooling fluid temperature and part loads become the primary parameters for determining the performance of the chiller. See **Figure 2**. These two parameters are application specific and are variable round the year. Moreover, different types of chillers behave differently under these two variable parameters. Under the same operating conditions one particular type may be more efficient than another type but the reverse may be true for the same chillers under some other operating conditions.

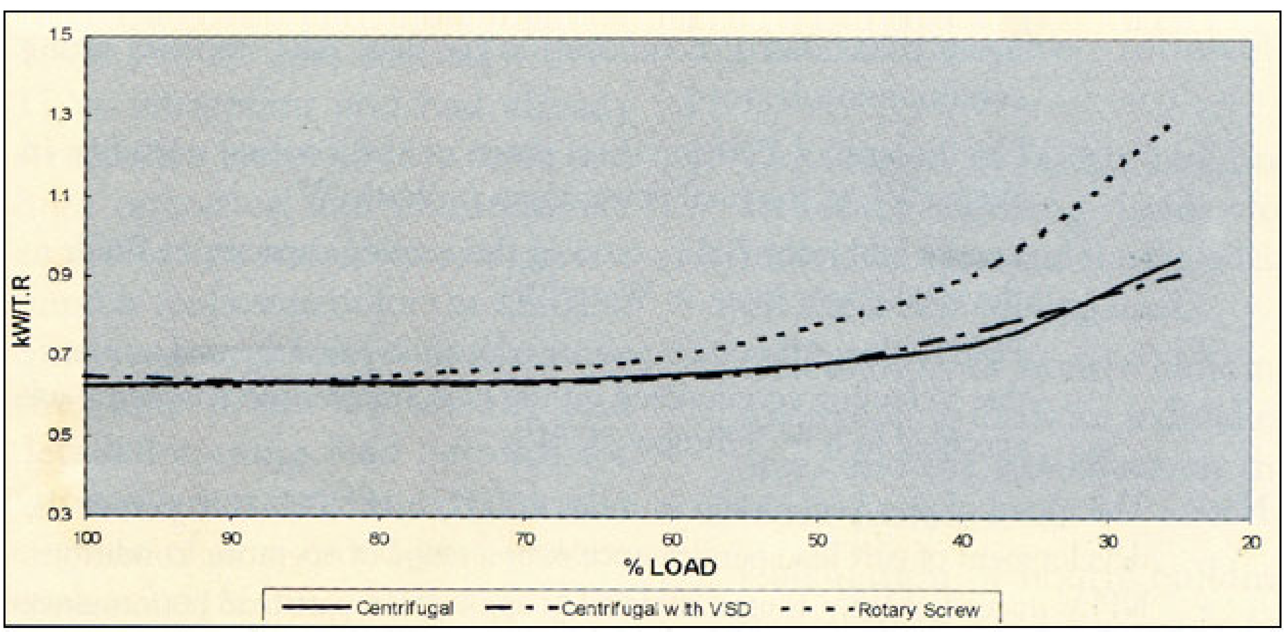

Figure 2 : Typical Part Load performances of chillers at fixed cooling water temperatures

At any time, a chiller can operate at the following two different operating conditions:

- Part load with lower cooling fluid temperatures.
- Part load with higher cooling fluid temperatures. As per ARI Standard 550/590 (1998), a chillers' part load values are evaluated as follows:
- Determine the part load energy efficiency at 100%, 75%, 50% and 25% load points at the conditions specified in **Table 1**.
- Use the following equation to calculate the IPLV or NPLV.

Table1 : Part Load Conditions for Rating as per ARI Standard 550/590(1998)

	IPLV	NPLV
Evaporator (All Types)		
100% Load LWT	44°F [6.7°C]	Selected LWT
0% Load LWT	44°F [6.7°C]	Same as 100% load
Flow Rate (gpm)	2.4 gpm/ton [0.043 L/s per kW]	Selected gpm/ton [L/s per kW]
Field fouling allowance (F.F.A.)	0.0001	As specified
Condenser (Water Cooled)		
100% load EWT	85°F [29.4°C]	Selected EWT
75% load EWT	75°F [23.9°C]	} Linear Variation upto 65°F
50% load EWT	65°F [18.3°C]	65°F (18.3°C)}
25% load EWT	65°F [18.3°C]	65°F (18.3°C)
0% load EWT	65°F [18.3°C]	65°F [18.3°C]
Flow rate (gpm) [L/s]	3.0 gpm/ton [0.054L/s per kW]	Selected gpm/ton [L/s per kW]
F.F.A.	0.00025	As specified

Assumptions:

1. The flow rates are to be held constant at full load values for all part load conditions.
2. For part load entering condenser water temperature, the temperature should vary linearly from the selected EWT to 65°F for 100% to 50% loads, and fixed at 65°F for 50% to 0% loads.
3. Chiller Operates at:
   100% load for 1% time per annum
   75% load for 42% time per annum
   50% load for 45% time per annum
   25% load for 12% time per annum
   LWT – leaving Water (liquid) temperature
   EWT – entering Water (liquid) temperature
   IPLV – Integrated Part Load Value, a single number part-load efficiency figure calculated as per ARI standard rating conditions.
   NPLV – Non-Standard Part Load Value, a single number part-load efficiency figure calculated at conditions other than ARI standard rating conditions.
   COP – Coefficient of Performance, ratio of the cooling capacity in Watts(W), to the total power input in Watts(W).

EER – Energy Efficiency Ratio, ratio of the cooling capacity in Btu/h to the total power input in Watts(W).
F.F.A – Field Fouling Allowance, provision for anticipated thermal resistance due to fouling accumulated on the heat transfer surface during use specified in h.ft² °F/Btu[m² °C/W].

Note: The intent of part load ratings in terms of IPLV and NPLV is to permit the development of part load performance over a range of operating conditions. NPLV instead of IPLV is used to develop application part load performance at conditions other than ARI standard rating conditions.

For COP and EER

IPLV or NPLV = 0.01A + 0.42B + 0.45C + 0.12D

where:

A = COP or EER at 100%

B = COP or EER at 75%

C = COP or EER at 50%

D = COP or EER at 25%

For kW/Ton

IPLV or NPLV = 1 / {(0.01/A) + (0.42/B) + (0.45/C) + (0.12/D)}

Where:

A = kW/Ton at 100%

B = kW/Ton at 75%

C = kW/Ton at 50%

D = kW/Ton at 25%

The prevalent criteria for the performance evaluation of chillers, as laid down by ARI has the following limitations:

1. ARI standard assumes that when the cooling load is low, the cooling fluid temperature is correspondingly lower. This assumption is seldom true, since cooling load does not depend solely on the ambient conditions but it has additional dependence on solar radiation, occupancy, ventilation, lighting, equipment etc. See **Figure 3**.
2. ARI assumption of part load operation times and values is based on the weighted average of the most common building types and operations using average weather in 29 U.S. cities.
3. ARI standard does not take into account variations in internal heat loads.
4. Combined operation of more than one chiller is not considered.

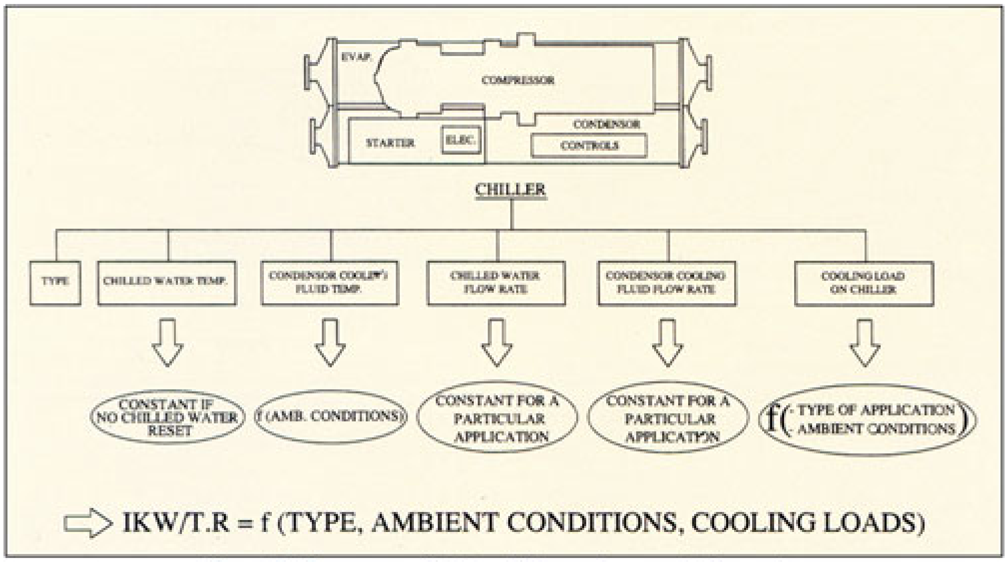

Figure 3 : Parameters affecting chiller performance (efficiency)

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Due to the above assumptions, criteria laid down by ARI for the performance evaluation of chillers can only give non-application specific results.

Thus, for determining the type of chiller which will be most efficient for a particular application, year round evaluation of the following two parameters needs to be done:

- Year round hourly cooling load variation.
- Determination of condenser cooling fluid (water or air) temperature coincident with each cooling load value.

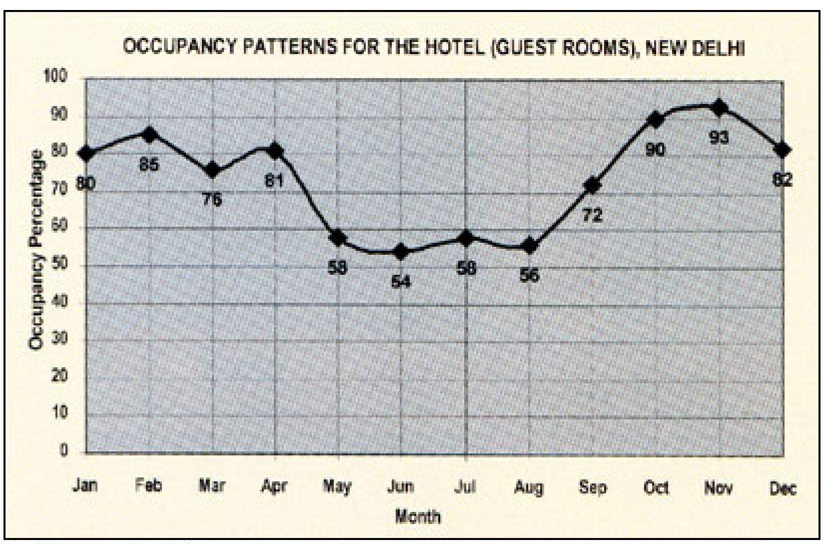

Figure 4 : Occupancy patterns for the hotel (guest rooms), New Delhi

Case Study

An existing prestigious five star hotel located in New Delhi had their centrifugal chillers installed in 1978. These chillers were selected with R- 11 as refrigerant and had already served their useful life, as a result had high operation and maintenance cost. Our firm was asked to suggest a suitable replacement for the chillers. Since, as energy audit consultants for the same hotel, we already had detailed cooling load patterns for various areas, we undertook the exercise of year round performance evaluation for various types of chiller options considered and made our recommendation accordingly.

The hotel comprises of approximately 30,000m2 of covered area on eight floors. There are a total of 296 guest rooms in the hotel apart from restaurants, banquet halls, shops, lobby etc. In addition, there is a separate arrangement to provide conditioned fresh air to guest rooms for ventilation.

The hotel has the following features, which are typically true for large hotels in India:

- The block cooling load is low during summer and monsoon (on account of lowest occupancy and hence least area usage). Thus, for such an application, the cooling load is low when the cooling fluid temperatures are high. See **Figure 4**.
- During any typical day, the cooling load is maximum during evening hours when cooling fluid temperatures are lower.
- Most of the time, there is a combined operation of more than one chiller.

The peak block cooling load for the existing hotel is 800 tons and it has two working chillers of 400 tons each (centrifugal water cooled type). The year round cooling load variations along with coincident cooling fluid temperatures were analyzed and evaluated (for 8760 hours) using the following procedure:

1. Calculation of hourly building structure cooling loads for individual areas and the net effect on the block cooling load.
2. Calculation of hourly building solar cooling loads for individual areas and the net effect on the block cooling load.
3. Calculation of hourly building ventilation cooling loads for individual areas and the net effect on the block cooling load.
4. Calculation of hourly occupancy loads (as per the occupancy patterns - see **Figure 4** and usage hours for various areas of the hotel) for individual areas and the net effect on the block cooling load.
5. Calculation of hourly building lighting loads for individual areas and the net effect on the block cooling load
6. Hourly net effect of fixed cooling load on the block cooling load.

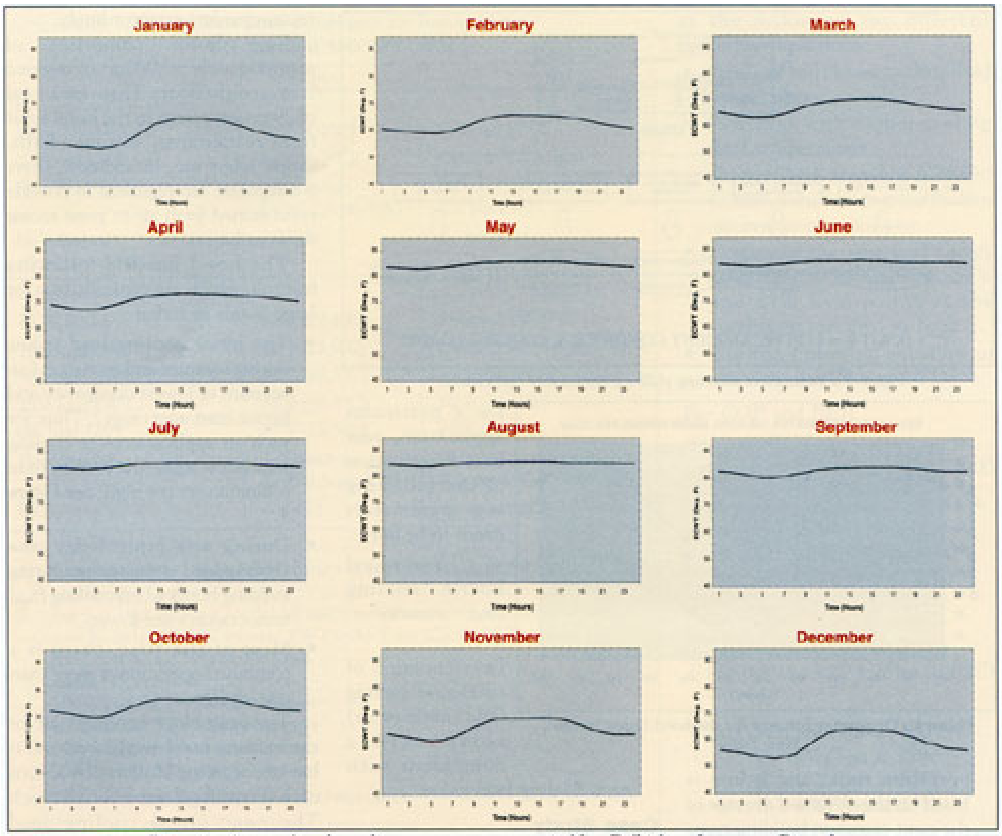

Figure 5 : Average hourly cooling water temperatures in New Delhi from January to December

Note: For ease of presentation, only average hourly cooling water temperatures for each month are shown. While, actual hourly cooling water temperatures for each day during the whole year have been used for evaluation i.e. for each of the 8760 hours.

Click to view the clear picture

Using the above procedure, the hourly net block cooling loads were evaluated for 8760 hours (365 x 24). The performance of each chiller type was worked out based on the following procedure:

- Calculation of hourly coincident cooling fluid temperatures for 8760 hours. See **Figure 5**.
- Evaluation of year round power consumption for each chiller type using hourly block cooling loads and coincident cooling fluid temperatures.

None of the chillers operated when there was no cooling load requirement i.e. during winters, taking into account the effect of ambient conditions, internal and external heat transfer etc.

For each chiller type, considering flow rate through condenser and evaporator as constant, the efficiency dependence in terms of Entering Cooling Water Temperature (ECWT) and part load is known from various manufacturers. Thus, at each value of block cooling load (hence, part load on the chiller) and coincident cooling fluid temperatures, hourly power consumption for each chiller type was obtained from the manufacturers.

Typical part load power consumption at various entering cooling water temperatures for 400 ton Centrifugal, Rotary Screw and Centrifugal Chiller with VSD are as shown in **Tables 2, 3 & 4**. At each hour, block cooling load and hence, part load on each chiller is evaluated while simultaneously obtaining coincident cooling fluid temperatures from the hourly weather data. This combined information is utilized to determine hourly specific power (kW/Ton) and hence the total power consumption for each chiller type from the available part load performance characteristics (refer Power Consumption Tables **2, 3 & 4**).

Table 2 : Power Consumption - kW/ton (Centrifugal Chillers)

% Loading

ECWT	100%	87.50%	75%	62.50%	50%	37.50%	25%
90 DEG F	**0.625**	0.633	0.635	0.652	0.686	0.750	0.950
86 DEG F	0.605	0.597	0.601	0.618	0.652	0.714	0.835
82 DEG F	0.571	0.565	**0.571**	0.588	0.621	0.681	0.803
78 DEG F	0.539	0.536	0.544	0.561	0.593	0.652	0.775
74 DEG F	0.511	0.510	0.519	0.536	**0.566**	0.623	0.748
70 DEG F	0.484	0.485	0.494	0.510	0.539	0.595	0.724
66 DEG F	0.459	0.462	0.470	0.484	0.512	0.567	**0.700**

Table 3 : Power Consumption - kW/ton (Rotary Screw Chillers)

% Loading

ECWT	100%	87.50%	75%	62.50%	50%	37.50%	25%
90 DEG F	**0.627**	0.629	0.663	0.687	0.780	0.941	1.310
86 DEG F	0.585	0.589	0.617	0.635	0.720	0.862	1.190
82 DEG F	0.543	0.552	**0.570**	0.587	0.660	0.783	1.080
78 DEG F	0.500	0.520	0.527	0.544	0.595	0.697	0.960
74 DEG F	0.475	0.497	0.487	0.496	**0.530**	0.625	0.840
70 DEG F	0.458	0.468	0.447	0.448	0.475	0.559	0.750
66 DEG F	0.440	0.434	0.413	0.417	0.445	0.513	**0.670**

Table 4 : Power Consumption - kW/ton (Centrifugal Chillers with VSD)

% Loading

ECWT	100%	87.50%	75%	62.50%	50%	37.50%	25%
90 DEG F	**0.652**	0.634	0.630	0.644	0.682	0.782	0.912
86 DEG F	0.598	0.578	0.572	0.587	0.610	0.679	0.846

82 DEG F	0.547	0.527	**0.518**	0.543	0.557	0.598	0.719
78 DEG F	0.499	0.479	0.467	0.466	0.497	0.528	0.621
74 DEG F	0.452	0.433	0.420	0.415	**0.439**	0.463	0.531
70 DEG F	0.408	0.388	0.376	0.366	0.365	0.400	0.452
66 DEG F	0.370	0.347	0.333	0.322	0.318	0.341	**0.382**

Notes on Power Consumption Tables 2, 3 & 4

1. *The power consumption values shown in bold are at ARI standard rating conditions.*
2. *For explanation purpose, part load power consumption is shown for every 12.5% unloading. While, for actual working, power consumption has been considered for every 2.5% unloading to get more accurate results.*
3. *The power consumption profile is similar as shown in tables for most of the standard makes whose data is available.*

Results of Case Study*

The specific and annual power consumption for different types of chillers viz rotary screw, centrifugal and centrifugal with VSD were worked out using the procedure as described above and ARI standard 550/590 (1998)

1. **Results based on hourly cooling load and coincident cooling fluid temperatures.**

   Annual cooling load = 1,812,825 ton hours (as obtained from the hourly simulation).

Type of Chiller	**IkW / ton	Total Energy Consumption per Annum (kWh)
Rotary Screw Chiller	0.603	1,093,634
Centrifugal	0.589	1,067,853
Centrifugal with VSD	0.516	935,852

2. **Results based on ARI standard 550/590 (1998):**

Annual cooling load = 1,812,825 ton hours (as obtained from the hourly simulation)

Type of Chiller	**IkW / ton	Total Energy Consumption per Annum (kWh)	Variation w.r.t. hourly simulation procedure
Rotary Screw Chiller	0.499	904,962	– 17.25%
Centrifugal	0.544	986,177	– 7.65%
Centrifugal with VSD	0.378	685,610	– 26.74%

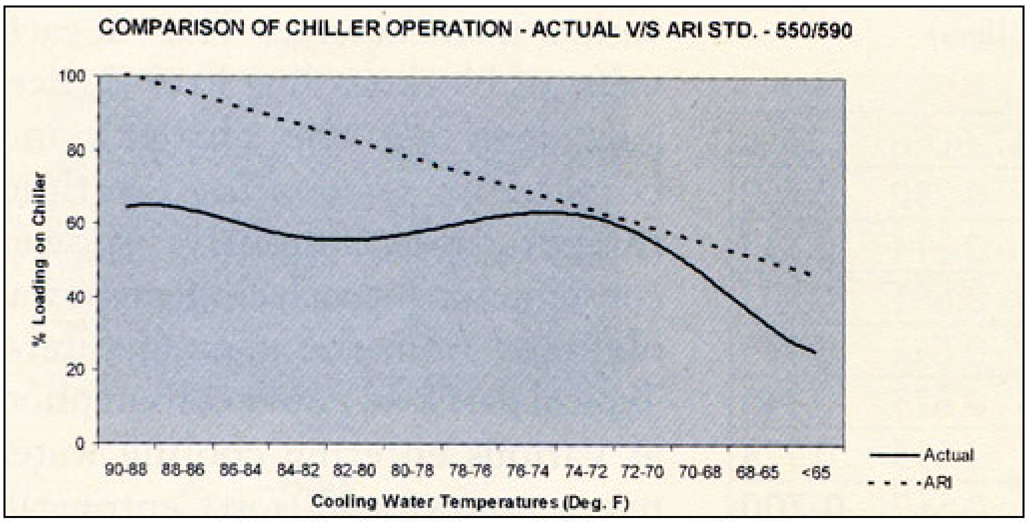

Figure 6 : Comparison of chiller operation – actual v/s ARI Std. – 550/590

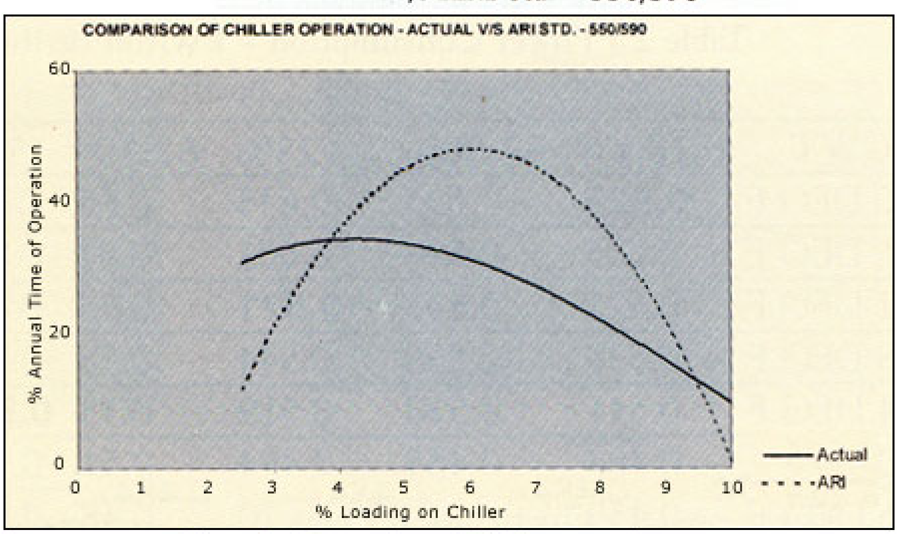

Figure 7 : Comparison of chiller operation – actual v/s ARI Std. – 550/590

Notes and Remarks on Comparison of Chiller Operation Curves, Figures 6 &

7

1. *As the curves indicate. ARI Std.–550/590 assumes a linear relationship between cooling water temperatures and percentage load on chiller i.e. at part cooling loads upto 50%, the cooling water temperatures are correspondingly lower. While, for part loads lower than 50%, a fixed cooling fluid temperature of 65°F is assumed.*
2. *For presentation purpose, actual percentage loading on chiller has been represented with an average value for every 2°F cooling water temperature. While, percentage loading for evaluation has actually been worked out at each of the hourly cooling water temperature values.*
3. *As evident from the Annual percentage time of operation, there is appreciable difference between the ARI and Actual curves. This is on account of two working chillers and hence more operation time at higher percentage loading. For comparison purpose, Actual percentage operation timing curve has been averaged out at same percentage loading points as that of ARI standard percentage loading points.*

Conclusion

Based on the above case study for the hotel, it is concluded that overall performance characteristics of different types of chillers differ significantly than as predicted by ARI standard 550/590 (1998). See **Figure 6 and 7**. This difference is primarily owing to higher cooling fluid temperatures at lower part loads and vice versa. Moreover, it is also inferred that, generally, screw chillers are less efficient than normal centrifugal chillers at part loads when the cooling fluid temperatures are higher. Also, at any given cooling fluid temperature, all positive displacement type of chillers are less efficient at part load than at full load, see **Figure 2**. However, non positive displacement type of chillers have their best efficiencies at approximately 80% part load.