Side-by-Side Field Comparison of New and Rebuilt CFC-Free Chillers

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A large electric utility in Southern California has performed side-by-side field testing comparing the performance of a new non-CFC chiller and a rebuilt centrifugal chiller that uses a CFC-free refrigerant. The first phase of the test was to replace one of the two 250-ton CFC-11 centrifugal chillers in the Ritz-Carlton Hotel with a new 250-ton HCFC-123 chiller and compare its performance with the existing CFC-11 chiller. Results showed that the new HCFC-123 chiller lowered the electric demand by 24 percent and the energy usage by 22 percent. The second phase of the test was to convert the remaining CFC-11 chiller to operate with a CFC-free refrigerant and compare its performance to the new HCFC-123 chiller. The original 250-ton CFC-11 chillers were operated at 0.8 kW/ton at full load. To obtain optimum performance, the impeller of the second original chiller was machined to reduce its size and the CFC refrigerant was replaced with HCFC-123. The capacity of the converted chiller was reduced by 7.4 percent with no effect on chiller performance. This project presented a unique opportunity to assess the side-by-side performance of both a new and converted HCFC-123 chiller.

INTRODUCTION

Background

Chlorofluorocarbons (CFCs) have been extensively used in air conditioning and refrigeration systems worldwide. However, since CFCs have been implicated in the depletion of the earth's ozone layer, regulations have been enacted that phased out their production by December 31, 1995 (Calm, 1993, White House, 1992). Ultimately the owner must choose one of three alternatives: Maintain the existing CFC chiller, retrofit the existing chiller for a non-CFC refrigerant, or replace the older CFC chiller with a new non-CFC unit (Calm, 1992). Thanks to advanced design, today's new electric non-CFC chillers are 45% more efficient than those 20 years ago (Shepard, 1995). With chiller impeller and drive-train modifications, existing CFC chillers can be converted to non-CFC refrigerant without loosing efficiency (Siebert, 1993). In some cases, the conversion may even improve the chiller performance (Watts, Lord, and Pancygrau, 1994).

To assess the energy and environmental benefits associated with such a chiller replacement, a large electric utility in Southern California selected the 240-room Ritz-Carlton Hotel in Rancho Mirage, California, as a test site for a two-phase chiller replacement project.

Scope

The hotel was originally served by two 250-ton CFC-11 centrifugal chillers. In June 1993, one of the chillers was replaced with a new 250-ton HCFC-123 centrifugal chiller. The central plant was monitored for one year to assess the performance of the new non-CFC chiller on a side-by-side basis with the remaining CFC-11 chiller.

In May, 1995 the remaining CFC-11 chiller was converted to use HCFC-123 as its refrigerant. To improve the chiller performance, the conversion included the re-machining of the chiller impeller and gear train replacement. Based on the peak cooling load from the project's first phase, the hotel only required 450 tons of cooling, thereby allowing the ‘‘optimum’’ conversion of the CFC chiller by trading chiller capacity for performance improvement. This presented a unique opportunity to assess the side-by-side performance of both a new and converted HCFC-123 chiller. The plant was then monitored with the identical equipment configuration until December 1995. The overall data capture rate for the monitoring period was 99 percent.

The analysis of the entire project encompassed not only the energy (kWh) and demand impacts (kW), but also the economic and environmental implications associated with each of the three chiller options.

Description of existing plant. All building cooling is provided via the central plant. Cooling is typically required 24 hours per day, 365 days per year. At the outset of the project, the primary central plant equipment consisted of two 250-ton electric centrifugal chillers, a nominal 485-ton (heat rejection) cooling tower, and associated chilled water and condenser water pumps. The chillers were piped in parallel and supplied chilled water to the building via three constant speed chilled water pumps, one of which was a backup. Heat was rejected from the chillers to a common two-speed cooling tower through a set of two constant-speed condenser water pumps.

The plant was controlled through a combination of automatic and manual controls. Chillers were staged ''on'' and ''off'' through an automatic control panel which also changed the ''lead'' and ''lag'' position of the chillers at a predefined interval. A separate control panel which was intended to stage the pumps was no longer operational. As a result, pumps were operated manually. In general, one chiller water pump was run for each operating chiller. One condenser water pump operated during the colder winter months and both operated during the warmer summer months, regardless of the number of chillers operating.

The cooling tower was slightly undersized for the system. During extremely hot and humid weather, chiller plant output was limited by the cooling tower capacity. Chilled water set points were often raised during peak cooling days to prevent the chillers from shutting down due to high head pressure.

Monitoring equipment description and configuration. The schematic diagram of the central plant including the monitored points is shown in Figure 1. In all, 22 monitored points consisting of nine RTD temperature sensors, one relative humidity sensor, six flow sensors, and six power (kW) transducers were used for this study. Table 1 shows the accuracies of the various sensor and transducers.

A positive displacement flow meter was utilized to measure the cooling tower make-up water, and turbine flow meters were utilized for monitoring the chilled water and condenser water flow rates through each chiller.

Figure 1. *Central Plant Schematic*

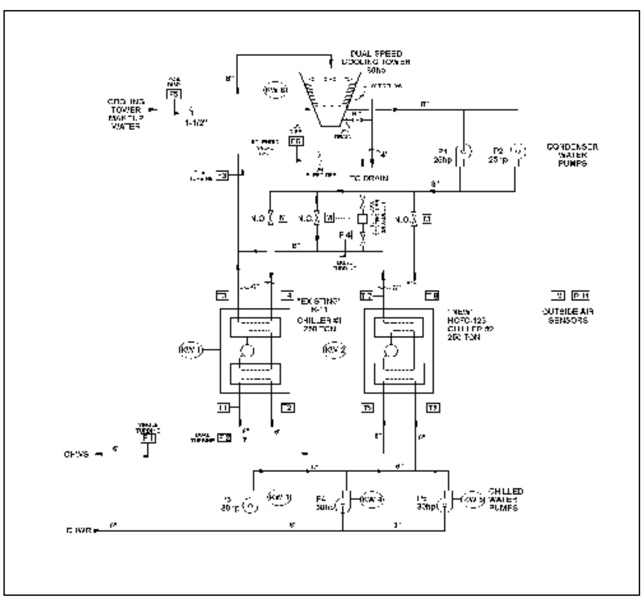


Table 1. *Sensors and Transducers*

Sensors	Type	Accuracy
Flow Meter	Dual Turbine Insertion	± 2.0%
Water Meter	Positive Displacement	± 1.5%
Temperature	RTD	± 0.1°F
Relative Humidity	Thin-Film Polymer Capcitor	± 2.0%
Electric Power	Watt-Transducer	± 1.5%

Immersion RTD temperature sensors with 0.1°F accuracy were installed in existing thermometer wells on the chilled water and condenser water lines of both chillers. The outdoor ambient conditions were monitored with a relative humidity sensor utilizing a thin film polymer capacitor and an RTD temperature sensor.

The logger had the capability of monitoring true RMS line voltage, line current, and both real and apparent power. Power was monitored for each of the chillers, chilled water pumps, and the cooling tower fan. Data was recorded as average volts, amps, and kilowatts on a 15-minute interval for each of the loads monitored.

The 15-minute interval monitored data was averaged and stored in the data logger, which was equipped with an internal modem for remote data retrieval. Data was collected daily for the first two weeks to ensure proper system operation. Thereafter, it was collected weekly for error checking and performance diagnostics.

METHODOLOGY

Demand and Energy Savings

The total central plant energy (kWh) and demand (kW) were evaluated for four separate plant configurations including the original base plan. These alternative configurations represent the three possible combinations of non-CFC chiller alternatives which could have been considered for the site. A description of each configuration is provided below:

Base. This base case represents the original as-designed central plant with two CFC-11 chillers.

Table 2. Annual Average Emission Rates (lbs/MWh)

Year	NO_x	SO_x	PM_{10}	CO_2
1994	1.53	1.06	.05	1208
1995	1.45	.96	.05	1203

Figure 2. Analysis Procedure Flowchart

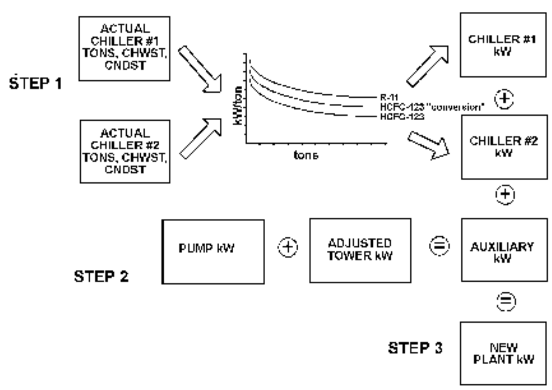
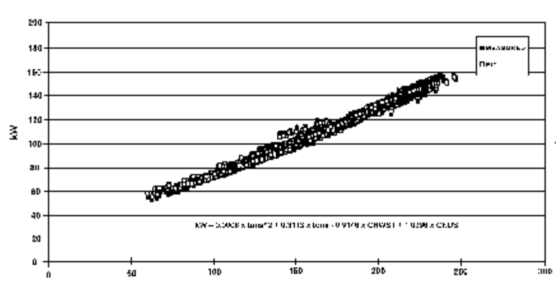


Figure 3. New HCFC-123 Chiller and Curve Fit



Alternate 1: This alternative is a central plant with two converted HCFC-123 systems.

Alternate 2: represents the current central plant configuration with one new HCFC-123 chiller and one HCFC-123 conversion chiller.

Alternate 3: This alternative represents a central plant in which both CFC-11 chillers are replaced with new high-efficiency HCFC-123 chillers.

A flowchart illustrating the analysis methodology for determining the demand and energy consumptions for each alternative is shown in Figure 2. The procedure consisted of three major steps:

Step 1: Calculate the chiller electric demand. The chilled water loads (in tons) were integrated over a 15-minute period using the monitors flow rates and temperature differential across each chiller. This load together with the actual operating conditions of the chiller was then used to calculate an electric demand using the regression curve fits that had been developed for each chiller type. Figure 3 shows the regression curve and fitting equation for the new HCFC-123 chiller. Inputs to the regression include the load, chilled water supply temperature, and condenser water temperature. Note that this methodology assumes that the operating conditions and relative loading on each chiller will be unchanged for each central plant configuration.

Step 2: Calculate the auxiliary electric demand. The auxiliary electric demand consists of chilled water pump, condenser water pump, and cooling tower fan power. Since the methodology assumes that relative loading and operation of the chillers will be unchanged, the chilled water and condenser water pumping power will remain as monitored. However, the efficiencies of the chillers are different, the cooling tower fan electricity must be adjusted to reflect the increase or decrease in condenser load associated with each chiller configuration. In the case where the cooling tower was running at full speed (~ 30 kW), no credit or penalty was taken for reduced cooling tower electric demand. This is a conservative estimate since the reduced cooling tower load would reduce the cooling tower temperature and indirectly result in improved chiller performance. The current cooling tower is undersized, and, as a result, it is unable to hold its 80°F set point for much of the summer despite running at full speed.

Step 3: Calculate the total plant electric demand. Finally, the total central plant electric demand was obtained by adding the chiller electric demand (Step 1) and the adjusted auxiliary electric demand (Step 2). This methodology was repeated for each of the four chiller configurations described previously.

Site Water Savings

The new chiller with better performance rejects less heat to the cooling tower. As a result, both cooling tower make-up water and chemical water treatment will be saved. Site water savings were determined on a monthly basis using a two-

Table 3. Electric Savings Summary

	Summer			Winter			Summer			Winter			
	On-Peak kW	Mid-Peak kW	Off-Peak kW	Mid-Peak kW	Off-Peak kW	Super Off kW	On-Peak kWh	Mid-Peak kWh	Off-Peak kWh	Mid-Peak kWh	Off-Peak kWh	Super Off kWh	Total kWh
Alternative 1: Two converted HCFC-123 chillers													
1994 Max/Sum	24	24	27	24	29	15	21,750	28,460	20,700	47,000	16,370	15,140	149,420
1995 Max/Sum	25	25	27	25	29	27	22,140	28,570	22,630	48,580	16,910	15,370	154,200
Avg. Yearly	25	25	27	25	29	21	21,945	28,515	21,665	47,790	16,640	15,255	**151,810**
Alternative 2: One new and one converted HCFC-123 chiller													
1994 Max/Sum	51	64	48	62	39	41	36,510	44,220	30,390	82,360	25,100	22,020	240,580
1995 Max/Sum	57	53	47	47	41	37	37,430	44,630	32,420	86,250	26,570	23,290	250,610
Avg. Yearly	54	58	48	55	40	39	36,970	44,425	31,405	84,305	25,835	22,655	**245,595**
Alternative 3: Two new HCFC-123 chillers													
1994 Max/Sum	75	106	61	77	49	48	48,180	56,750	38,200	102,820	30,510	26,680	303,110
1995 Max/Sum	81	75	61	58	49	46	57,000	67,730	52,100	102,550	31,030	27,380	337,780
Avg. Yearly	78	91	61	67	49	47	52,590	62,240	45,150	102,685	30,770	27,030	**320,445**

step process. First, the overall water consumption rate was determined by dividing the make-up water consumption (gallons) by the total condenser load (ton-hours) for the month. This factor (gallons/ton-hour) was then multiplied by the change in cooling tower load attributed to each chiller plant configuration. Note that the makeup water is inclusive of the water lost due to drift and the cooling tower drain down.

Emission Reductions

Annual average emission rates, lbs/MWh, (SCE,1993) of four pollutants (NO_x, SO_x, PM_{10}, and CO_2) were used to predict emission savings of the base case chiller plant (See Table 2). These savings represent reduced power plant emissions due to reduced electric energy consumption.

RESULTS

Chiller Performance

Centrifugal chiller performance is primarily a function of three parameters: part load operating ratio, chilled water supply temperature, and the condenser water temperature leaving the cooling tower. Figure 4 presents the actual monitored performance of each chiller type. The scatter in the data can be attributed to operation at varying chilled water and condenser water temperatures. To show the part load performance of the chillers at or around the ARI testing conditions, (ARI, 1992) the data was filtered to include chiller performance for chilled water temperatures between 41°F and 45°F and condenser water temperatures between 80°F and 85°F only. Clearly, part load operation has the most significant impact on chiller performance.

At low loads the retrofit chiller has a much better performance than the older CFC-11 chiller, while at full load these two chillers' performance is almost identical. The ARI-rated full load performance ratings of the existing CFC-11, retrofit, and new HCFC-123 chillers were approximately 0.85, 0.78, and 0.60 kW/ton, respectively.

Energy and Demand Savings

Table 3 summarizes the annual savings for each of the configurations relative to the base case of two CFC-11 chillers. The average summer on-peak demand savings for each of

Table 4. Monthly Water Use Summary

Month	Heat Rejected ton-hr	Makeup Water 1000's of gal	Blowdown Water 1000's of gal	Blowdown Ratio %	Makeup Rate gal/ton-hr	Water Savings Alt 1 100's gal	Alt 2 100's gal	Alt 3 100's gal
Jan	78,870	100	22	22	1.27	32	53	58
Feb.	118,410	170	25	15	1.44	34	65	71
Mar.	120,710	170	25	15	1.41	34	65	71
Apr.	123,020	182	34	18	1.48	41	83	83
May	140,330	200	59	30	1.42	36	43	78
June	166,870	245	72	29	1.47	61	90	115
July	237,100	303	45	15	1.28	69	107	133
Aug.	244,130	323	63	19	1.32	70	113	143
Sept.	219,600	243	57	24	1.10	54	86	112
Oct.	169,080	133	53	40	1.34	58	83	113
Nov.	128,730	63	40	64	1.34	36	68	77
Dec.	102,620	26	25	97	1.34	36	66	66
Total	1,849,470	2158	520	24	*1.34	566	922	1123

*Note that the average make-up and flow rates exclude October through December due to flow meter malfunction.

the three configurations were 25 (5.4%), 54 (11.8%), and 78 (17.0%) kW, respectively. The corresponding annual energy savings were 152 (6.7%), 246 (10.9%), and 302 (13.4%) MWh. Figures 5 and 6 illustrate the electric demand and energy savings.

Water Savings

A summary of the monthly water usage and savings is shown in Table 4. Water savings are a result of the reduction in condenser load associated with more efficient chillers as compared to the base CFC chillers. The annual cooling tower makeup water and blow down water consumption for 1995 was 2,158,000 and 520,000 gallons, respectively. As such, the blow down water flow represents approximately 24 percent of the total makeup flow. The average annual makeup water rate was 1.34 gallons/ton-hr based on a total condenser load of 1,849,000 ton-hrs., and a total water consumption of 2,158,000 gallons.

Utility Savings

Annual electric savings based on the utility's time-of-use rate schedule for each of the alternatives are summarized in Table 5. Total annual electric savings are $14,420 for the two converted HCFC-123 chillers, $18,420 for the one new HCFC-123 and one converted HCFC-123 chillers, and $24,760 for the two new HCFC-123 chillers.

As a result of the reduced condenser loads associated with the more efficient chiller operation, the Ritz-Carlton will also realize both water utility and water treatment savings. While these are not of the same magnitude as electric savings, they are appreciable. According to the operations engi-

Table 5. Electric Utility Savings

	Demand Savings ($)					Energy Savings ($)						
		Summer				Summer			Winter			
	Non-Time Related	On-Peak	Mid-Peak	Off-Peak	Winter	On-Peak	Mid-Peak	Off-Peak	Mid-Peak	Off-Peak	Super Off	Total Savings ($)
Alternative 1: Two converted HCFC-123 chillers												
1994 Total	860	1,960	210	0	0	3,140	1,950	890	3,790	750	690	14,220
1995 Total	860	2,020	240	0	0	3,190	1,950	970	3,920	770	700	14,610
Avg. Yearly	860	1,990	220	0	0	3,160	1,950	930	3,850	760	690	**14,420**
Alternative 2: One new and one converted HCFC-123 chiller												
1994 Total	1,650	4,110	490	0	0	2,500	1,890	2,450	3,750	1,140	0	17,990
1995 Total	1,690	4,440	500	0	0	2,560	1,910	2,610	3,930	1,210	0	18,860
Avg. Yearly	1,670	4,280	500	0	0	2,530	1,900	2,530	3,840	1,180	0	**18,420**
Alternative 3: Two new HCFC-123 chillers												
1994 Total	2,290	5,800	720	0	0	3,300	2,430	3,080	4,680	1,390	0	23,690
1995 Total	2,110	5,970	670	0	0	3,900	2,900	4,200	4,670	1,410	0	25,830
Avg. Yearly	2,200	5,890	700	0	0	3,600	2,670	3,540	4,680	1,400	0	**24,760**

Table 6. Water Utility Savings

Alternative	Water Consumption Savings ($)	Water Treatment Savings ($)	Total Water Savings ($)
Two converted HCFC-123	90	80	170
One converted and one new HCFC-123	140	120	260
Two new HCFC-123	170	150	320

Table 7. LCC Parameter Summary

Scenario	1	2	3
Discount Rate	10%	7.5%	5%
General Inflation	5%	5.0%	5%
Utility Escalation	0%	2.5%	5%

neer at the Ritz-Carlton, water treatment costs had averaged approximately $240 a month for the past two years. For analysis purposes, water treatment costs were assumed to be proportional to the water usage. Table 6 summarizes the annual water savings for each of the three central plant configurations. The annual savings range from $170 for the plant with two converted HCFC-123 chillers to $320 for the

Table 8. Life Cycle Cost Savings

Chiller Plant Configulations	First Cost	Annual Cost Savings	20-Year Life-Cycle Cost		
			Scen. 1	Scen. 2	Scen. 3
2 converted with HCFC-123	$ 99,410	$14,420	$24,720	$84,180	$192,190
1 converted, 1 new with HCFC-123	$164,010	$18,422	($4,890)	$71,340	$209,790
2 new with HCFC-123	$228,600	$24,764	($15,080)	$87,210	$272,990

Table 9. Emission Savings Summary

	NO_x lbs	SO_x lbs	CO_2 1000's of lbs	PM_{10} lbs
Alternative 1				
1994 Total	229	158	180	7.5
1995 Total	224	148	186	7.7
Avg. Yearly	226	153	183	7.6
Alternative 2				
1994 Total	368	255	291	12.0
1995 Total	363	241	301	12.5
Avg. Yearly	366	248	296	12.3
Alternative 3				
1994 Total	464	321	366	15.2
1995 Total	490	324	406	16.9
Avg. Yearly	477	323	386	16.0

Figure 4. *Typical Chiller Performance*

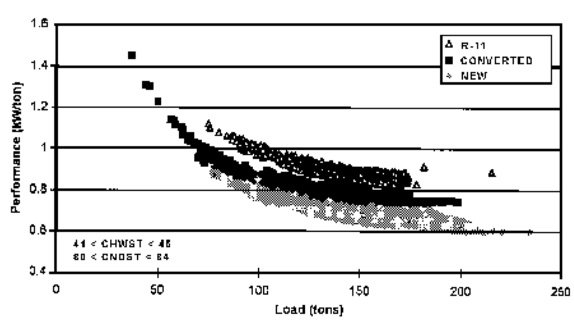


Figure 5. *Electric Demand Savings*

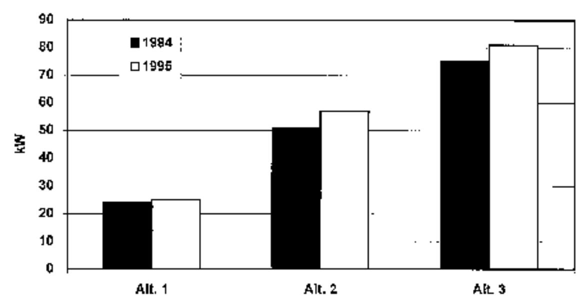
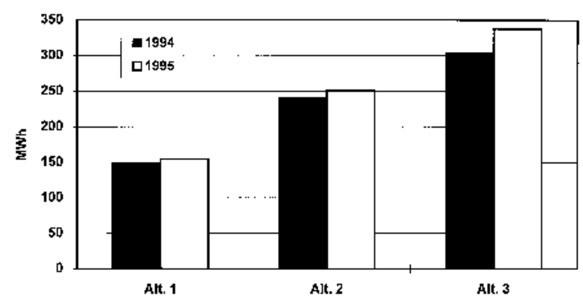


Figure 6. *Electric Energy Savings*



two new high-efficiency HCFC-123 chillers. Total annual utility savings (electric and water) for each alternative are illustrated in Figure 7.

Life Cycle Cost Analysis

A twenty-year life cycle cost analysis was performed for each of three non-CFC chiller plant configurations, encompassing a range of future economic conditions, including discount rate, utility escalation rates, and general inflation.

Scenario 1 assumes that utility costs escalate with general inflation and that the ''cost'' of money is relatively high.

Figure 7. *Total Utility Savings*

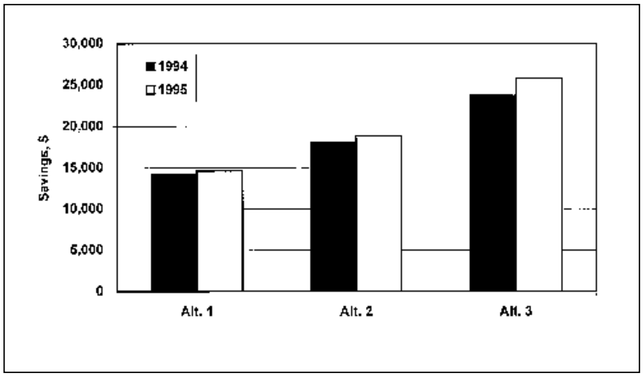
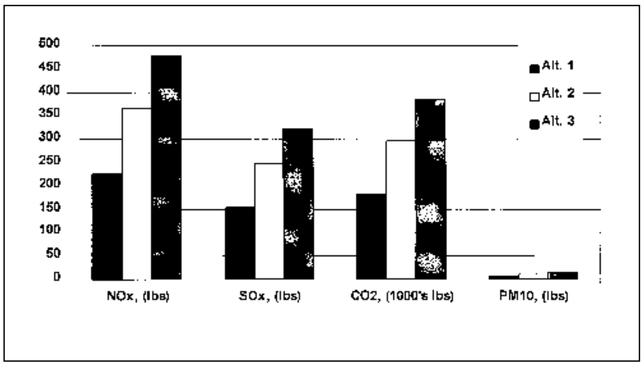


Figure 8. *Emission Savings Summary*



Scenario 2 and 3 assume that utility costs escalate faster than inflation and the cost of money is lower. Table 7 summarizes the discount rate, general inflation rate, and the utility escalation rates for each of the three scenarios. Note that the discount rate and utility escalation rates are the nominal rates before general inflation. Also, the chillers were assumed to have no salvageable value at the end of the 20-year period. Maintenance costs were assumed to be the same for all chiller plant configurations and have been excluded from the analysis. Note that while the prosect of competition in the utility may ultimately bring deflation to utility rates, life cycle costs are most sensitive to what occurs during the first few years of the analysis. Therefore, unless utility costs fall significantly quickly, the scenarios laid out above were likely provide a reasonable range of scenarios which a building owner would see today. Results of the life-cycle cost analysis are presented in Table 8. The first alternative, two converted chillers, has the lowest first cost at $99,410 but also the lowest utility savings. For the remaining two life-cycle cost scenarios, two new high-efficiency chillers are the best alternative.

Emission Savings

Table 9 provides an annual summary of the power plant emission savings attributed to the reduced energy consumption of the non-CFC chiller plants. Figure 8 illustrates annual average emission savings attributed to the savings of each alternative relative to the base CFC-11 plant.

CONCLUSIONS

Based on the test results, it can be concluded the following:

- Although HCFC-123 refrigerant is not as efficient as CFC-11, with appropriate design non-CFC chillers can be made more efficient than CFC chillers.

- An optimized engineered conversion can result in a significant efficiency improvement in existing CFC-11 centrifugal chillers, provided there is excess cooling capacity. For the chiller monitored in this study, this was particularly true under lower part loads.

- Given the relatively expensive electric utility rates in southern California, replacing an existing CFC-11 chiller with a new high efficiency HCFC-123 chiller (as opposed to retrofitting) is likely warranted from a life cycle cost vantage point if the chiller operates for a significant number of hours.

- In cases where a chiller serves primarily in a backup role, or has limited operating hours, maintaining the existing CFC-11 chiller or converting the chiller may be a more economical solution.

- The final decision as to whether to retrofit or replace an existing CFC chiller is dependent on a number of factors:

  —Incremental first cost between the new and retrofit chillers
  —Age and condition of existing chillers
  —Electric utility costs
  —Chiller utilization (i.e., number of operating hours, cooling demand)

The best chiller plant solution for a building owner should be made on a site-by-site basis.

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