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A case history study illustrating the need for energy economics in design

A comprehensive study of campus cooling points up the necessity of incorporating the energy economics parameter into the design of building systems, and specific recommendations tell how to go about it.

Chapter 48 entitled "Integrated Loop System For Campus Cooling" presents the background of a study that resulted in the recommendation to install an integrated loop chilled water system on the campus of the University of Missouri–Rolla.

Briefly, the recommendation called for existing chilled water plants serving individual buildings to be connected in a loop system. Because of system load diversity, they would thus be able to provide chilled water for additional buildings currently served by a variety of packaged equipment and window air conditioning units (see Fig. 23-1). This would be accomplished with significant savings in both energy consumption and machine operating hours as compared with the installation of separate central systems in the buildings now served by unitary equipment.

In the process of gathering the information needed to make this study (heating and cooling loads, types and sizes of refrigeration machinery and auxiliaries, types of building environmental systems, etc.), significant data were developed. These data serve as the basis of this chapter—a case history report on building energy economics comparison. The information is presented to accent the differences in energy demands and consumptions among various buildings with similar uses and occupancy schedules. The excesses of energy required by some indicate that although the buildings were all relatively successful designs architecturally and environmentally, energy economics was not considered as a design parameter.

This is not a unique situation. For the past three and one-half decades in the United States, the building environmental sciences have been undergoing probably a more dynamic progression than any other field of engineering in history, save space technology. As a result, design practitioners have had all they could cope with in keeping pace with progress in building materials, building systems, fenestrations, mechanical system concepts, and new machinery. In addition, they have had to meet the demands of the marketplace from the standpoint of ever-increasing requirements for multiple control zones. The additional pressure of satisfying these demands within the budget restrictions established for earlier, less sophisticated systems posed a challenge of almost astronomic proportions to the systems design profession. With these burdens, and with readily available

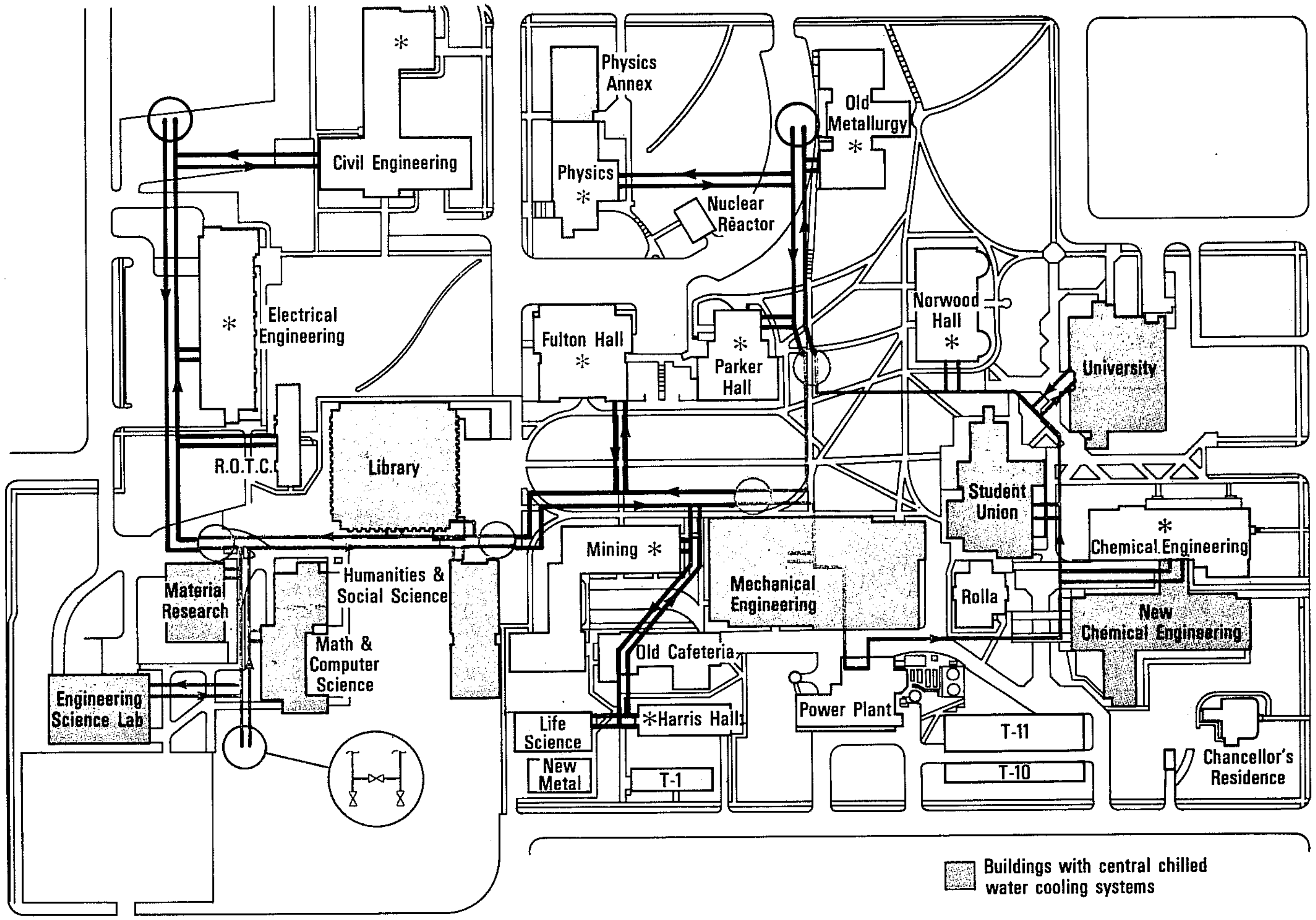

Fig. 23-1. Campus of the University of Missouri-Rolla. Buildings shown in color have central chilled water refrigeration plants. Colored and black piping together represent the proposed integrated loop system described last month. Phased construction was recommended, the piping shown in black representing the last stage of loop development pending further campus expansion and the circles on the piping denoting connections to be made as the loop is developed and expanded. Buildings marked with asterisks are those without central cooling, considered for inclusion in the integrated loop system.

and competitively priced energy sources, design practitioners understandably did not consider energy economics as a design parameter.

It might be emphasized at this point that building environmental systems include lighting as well as HVAC systems. Thus, a major portion of the total output of electric power generating plants serves building environmental needs. Other major areas of energy consumption are the categories of transportation and industrial processes, and neglect of energy economics is as manifest in these areas as it has been in the building industry.

Building loads compared

The Rolla campus includes ten buildings with central chilled water systems. Table 23-1 shows the comparative loadings of the ten buildings. They are seen to range from 147 sq ft per ton (82 Btuh per sq ft) for the Student Union to 594 sq ft per ton (20.2 Btuh per sq ft) for the Library. This comparison, however, is not especially revealing since occupant loading densities and functions are considerably different for these two buildings. If these two buildings and the University Center are discarded, the remaining buildings are similar in function, occupancy densities, and occupancy schedules. These range from 194 sq ft per ton (62 Btuh per sq ft) for the Mechanical Engineering Building to 413 sq ft per ton (29 Btuh per sq ft) for the Math & Computer Science Building.

An understanding of the differences in specific capacity requirements is essential if one is to make use of this information in the development of methods for minimizing energy usage. Although specific capacity is only one area of concern, it is the area that often is completely out of the control of the mechanical systems designer (except for the ventilation rate contribution). This specific loading is the calculated coincident full load that the building (plus ventilation) imposes on the system. Not included in this form are any inherent system inefficiencies, such as reheat, refrigeration and heat energy in reduced load zones at the time of maximum building coincident load, distribution system losses, etc.

Lighting levels range from 1.63 W per sq ft for the Library to 3.64 W per sq ft for the Materials Research Building. (The values are based on total installed lighting per gross area.) Again, if the nonsimilar use buildings are discarded, the range is 2.44 W per sq ft for the New Chemical Building to 3.64 W per sq ft for the Materials Research Building. The correlation between lighting power density and specific cooling load, however, while not overly impressive, is significant; a calculation for the seven similar use buildings reveals a positive correlation of 0.4. This is not surpris-

Table 23-1. Calculated cooling loads versus installed capacities for buildings with central chilled water plants.

Building	Area, sq ft	Cooling load, tons	Installed capacity, tons	Load, sq ft per ton
Physics Annex	14,800	37	71	400
New Chemical Engineering	78,600	268	360	293
Library	85,600	144	274	594
Mechanical Engineering	38,922	200	200	194
Student Union	17,900	122	115	147
University Center	38,400	166	204	231
Materials Research	28,600	101	120	283
Math & Computer Science	35,900	87	123	413
Humanities & Social Science	30,600	123	155	249
Engineering Science Lab	42,400	155	195	274
Totals/average	411,722	1403	1817	293

ing since any building design feature that adds to the cooling load should obviously be scrutinized if energy economics are being considered.

Another feature that has an appreciable effect on cooling load but was rejected from a quantitative analysis is the fenestration of the different buildings. A correlation between fenestration and specific cooling load for these buildings was similar to the lighting level correlation ($r = 0.36$). But since all relevant variables were not considered (such as reflectivity of glass, interior shading methods, and exterior shading versus orientation), this feature was not included.

Effect of auxiliaries

Thorough understanding of the building features that contribute to specific cooling load is the very starting point in designing with energy economics as a parameter. If the total cooling load increases, the base power requirement to drive compressors (W) or absorption machines (Btuh) increases, the power requirement to drive all necessary auxiliaries increases, and the resulting energy consumption increases. As stated previously, the Mechanical Engineering Building, at 62 Btuh per sq ft, has more than twice the specific cooling load of the Math & Computer Science Building, at 29 Btuh per sq ft.

The mechanical systems designer is seldom in a position to control the specific cooling load, a topic that will be discussed again in a subsequent section. He is in sole control of the energy usage per unit of building requirements, however. Specific system power requirements, SSP, is defined as the power per unit of cooling capacity as required by system design, expressed in such units as Btuh per ton or kW per ton. Specific system energy, SSE, is the seasonal or annual energy consumption per unit of system capacity requirement, expressed in such units as Btu per ton or kW-hr per ton.

All of the buildings studied have absorption chillers, except for the Student Union with an electric centrifugal compressor. Specific system power requirements and specific energy requirements were analyzed for the ten building systems, and Table 23-2 illustrates the comparative mechanical system power requirements. The refrigeration auxiliaries include chilled water pumps, condenser water pumps, cooling towers, absorption unit pumps, and control power. The fan auxiliaries

Table 23-2. Comparative mechanical system power requirements.

				Refrigeration auxiliary power		Total auxiliary power		
Building	Area, sq ft	Installed capacity, tons	Fan auxiliary power kW	kW	kW per ton	kW	kW per ton	W per sq ft
Physics Annex	14,800	71	8.8	22.1	0.3112	30.9	0.4352	2.0878
New Chemical Engineering	78,600	360	67.5	80.0	0.2222	147.5	0.4097	1.8765
Library	85,600	274	84.0	115.5	0.4215	199.5	0.7281	2.3306
Mechanical Engineering	38,922	200	42.1	66.5	0.3325	108.6	0.5430	2.7901
Student Union	17,900	115	12.0	27.7	0.2408	39.7	0.3452	2.2178
University Center	38,400	204	27.0	52.4	0.2568	79.4	0.3892	2.0677
Materials Research	28,600	120	7.5	24.0	0.2000	31.5	0.2625	1.1013
Math & Computer Science	35,900	123	54.3	44.4	0.3609	98.7	0.8024	2.7493
Humanities & Social Science	30,600	155	23.1	28.1	0.1821	51.2	0.3303	1.6732
Engineering Science Lab	42,400	195	76.0	45.6	0.2338	121.6	0.6235	2.8679
Totals/averages	411,722	1817	402.3	506.3	0.2786	908.6	0.7787	2.2141

include only the supply and return air fans (fans necessary to effect space conditioning). These power loads are then brought to a specific requirement by referring to the common denominator of installed tons.

Figure 23-2 illustrates these data in bar graph form.

It is important to note that if these power units were brought to the base of kW per building ton, they would be higher in many cases since installed capacities exceed building loads, partly because of system parasitic loads (required for control purposes) and partly because of available machine sizes. This is illustrated in the last column of Table 23-2, which expresses total system auxiliary power requirements per square foot of building area. (Note that this combines the specific load with specific power.) In this evaluation, building function does not have the relevance it did in comparing specific cooling loads, as long as the comparison is made in kW per system or installed ton.

Brief descriptions of building systems are given in Chapter 48 and will not be repeated here (but rudimentary information is given in

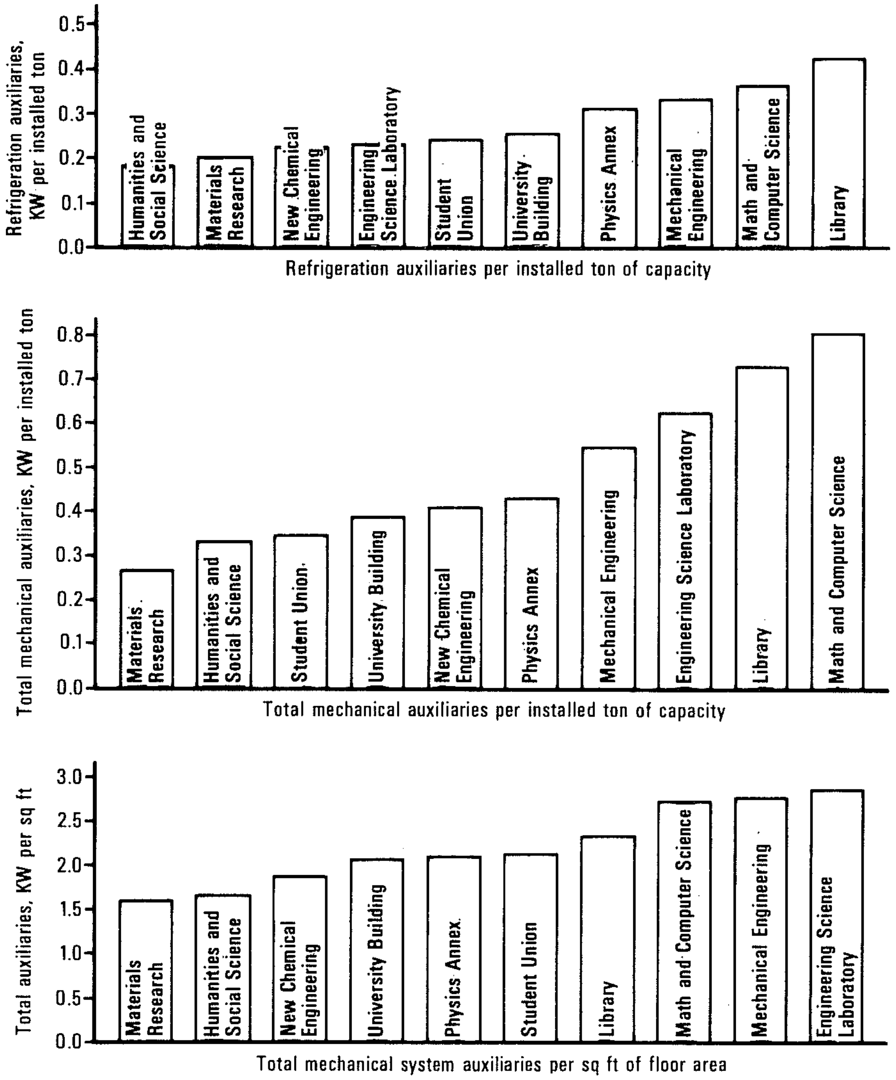

Fig. 23-2. Power inputs for mechanical system auxiliaries in the different buildings compared. Total mechanical auxiliaries include refrigeration auxiliaries and supply and return air fans.

Table 23-3). Before any value can be assigned to the data, however, one must understand the systems so as to determine the sources of deviations. Contributing factors included:

- Of the four buildings with the highest specific power requirements, three employed high-pressure air distribution systems.
- The cooling tower fan motors ranged from 0.065 to 0.275 hp per ton. The primary difference appeared to be higher horsepower requirements for less real estate. That is, when space limitations prevailed, power requirements increased.
- Chilled water pumps ranged from 0.02 to 0.21 kW per ton.
- Condenser water pumps ranged from 0.032 to 0.15 kW per ton.

Although the absolute values for the above specific requirements are small, they are significant in their deviations: 420 percent for cooling towers, 1050 percent for chilled water pumps, and 470 percent for condenser water pumps. When extended to system capacity, these deviations are *most* significant.

Annual energy consumption

Power, the time rate of energy production (or consumption), is a significant consideration in the cost of energy since power dictates the investment in generating plant and distribution system. When considering basic resources, however, the energy unit becomes the primary target.

Annual energy consumptions for the buildings were determined using a computerized calculation technique that has been verified in many buildings. The results are shown in Table 23-3, together with specific building energy requirements, SBE, for both electrical and thermal forms, and an identification of the type of terminal system control. (A combined result of specific energy and specific loading, each for the time period of one year, in units of KWH per sq ft and Btu per sq ft, is defined as the specific building energy consumption.)

Inspection of the results leads to the following observations:

- There is a positive correlation between

Table 23-3. Total annual electrical and thermal energy requirements of buildings studied. Aborption refrigeration is used in all buildings except the Student Union, which has an electric motor driven centrifugal.

			Annual energy consumptions				
Building	Area sq ft	System[1]	KWH × 10^{-3}	KWH per sq ft	Btu × 10^{-6}	Btu per sq ft	ΣSBE,[2] Btu per sq ft
Physics Annex	14,800	MZ	220.3	14.9	535	36,200	200,200
New Chemical Engineering	78,600	DD/VV	1201.1	15.3	3876	49,200	217,200
Library	85,600	DD	1590.2	18.6	3525	41,200	246,200
Mechanical Engineering	38,922	RH	622.8	16.0	3427	88,000	264,000
Student Union	17,900	HCO	348.5	19.5	106	59,200	273,400
University Center	38,400	MZ	681.1	17.7	4769	124,000	319,000
Materials Research	28,600	HCO	390.4	13.6	1250	43,700	193,000
Math & Computer Science	35,900	RH	749.7	20.9	5289	147,000	377,000
Humanities & Social Science	30,600	RH,HCO	439.3	14.3	4506	147,200	304,000
Engineering Science Lab	42,400	RH	971.9	23.0	7649	180,000	433,000

[1] MZ = multizone; DD = dual duct; DD/VV = dual duct with variable volume mixing boxes; RH = reheat; HCO = heat-cool-off.

[2] SBE = specific building energy consumption.

systems with higher specific electrical energy consumptions and those with higher specific power consumptions. (This correlation, though only on the order of 0.11, is positive and can be considered as having some significance.)

- Of the four buildings with the highest specific building electrical energy consumptions, three have high-pressure fan systems.
- *The building with the electric chiller does not have the highest specific building electrical energy consumption* (although it does rank third).
- The three similar use buildings with the highest specific building thermal energy consumptions all have reheat systems.

These results are not significantly different from what one would expect. The contribution of a high-pressure fan system to specific electrical energy consumption is obvious when one realizes that fan horsepower is directly proportional to pressure and that the fan operates for all the occupied hours of the building (i.e., it does not unload at reduced capacity, at least not in the systems installed in these buildings).

Analysis of a reheat system reveals that absolute energy consumption increases with decreasing building load. In dual stream and heatcool-off systems, on the other hand, energy consumption decreases with decreasing load. (With any energy conversion device, however, the consumption per unit of demand increases in an exponential manner with a decrease from full load.) Unfortunately, the humidity control capabilities of these three alternatives are inverse functions of their inherent system specific energy consumptions.

The last column in Table 23-3, titled summary specific energy (ΣSBE), is intended to illustrate specific energy consumption as a single quantity; it was developed using the arbitrary value of 11,000 Btu per delivered KWH for electrical energy. (The calculated thermal energy and electrical energy consumptions include all conversion losses and thus are the quantities delivered to the buildings.) From the standpoint of pure energy economics, this is the most relevant comparison. Since the conversions are arbitrary and subject to challenge, however, they are presented simply for interest. Attempts are currently being made to develop acceptable data for extension of this unit in building energy economics studies.

Energy economics

The Rolla study, which shows a differential of 123 percent between the similar use building with the lowest summary specific building energy consumption and that with the highest, exemplifies the need to include energy economics as a parameter in building environmental system design. The following considerations are offered as a positive approach to incorporating energy economics into the design of all building systems.

- *Energy consciousness in building design*—This consideration is not normally under the direct control of the mechanical engineer on the building design team. Since it has such a direct effect on investment cost as well as on energy consumption of environmental systems, however, he has an obligation to make architects and electrical engineers aware of the implications of their designs with regard to the energy aspects of the building. As was emphasized earlier, it is at this stage of design development that the very significant specific building load, is established.
- *Intelligent definition of design parameters*—Available analytical data have been published for some time to illustrate the specific energy requirements of the three basic system control methods. At full cooling load conditions, all three might have the same specific energy requirements. But at reduced load conditions (which an analysis of any building system will show to exist during a majority of the operating hours), the requirements of these systems differ significantly. In order of increasing energy consumption at reduced loading, they are: heat-cool-off and variable volume, dual stream (double duct or multizone), and reheat.

Unfortunately, if one lists the same three basic systems in order of their ability to maintain space humidity control, the order is reversed. Thus, it is the responsibility of the systems designer considering energy economics to establish intelligently the *real* building requirements vis-a-vis humidity ranges or limits and then design a system to provide that level of control and no more. This approach is quite revealing, and it leads to the concept of incorporating energy units into the ASHRAE comfort chart.

Additionally, the single fan "economizer" type system must be scrutinized carefully in the process of systems selection. In many applications (those involving multizone or dual duct installations), specific energy consumption with such a system is higher than when some reduced capacity refrigeration machinery is operated in cold weather periods. The logic is quite obvious: with a single fan "economizer" system, the heating deck becomes a reheat device, and thermal energy consumption increases.

- *Detailed load calculation and part load analysis*—As stated previously, any energy conversion system is less efficient at reduced load operation than at design loading. Thus, if a system is sized to a "safe" load calculation, it will operate at a lower percentage of full load, and a lower efficiency, at all times. The latest computerized techniques of calculating heating and cooling loads should therefore be employed. As an example, if a system or component is oversized by 25 percent, at peak load it will never operate above 80 percent of design capacity, a point of higher specific energy consumption than at full capacity.

The part or reduced load analysis is a very tedious one to perform, but computer programs are available to assist designers in this effort. A part load analysis will reveal the hours per year or the percent of total operating hours that the system will "see" various increments of the full load. By using this analysis in selecting machine size increments, the designer can assure the greatest number of operating hours at the greatest machine load ratios, thereby greatly decreasing specific energy consumption.

- *Flow rate analysis*—Although two-phase steam systems are still widely used for primary heat transfer, and for good reason, the majority of systems employ the single-phase hydronic concept for terminal fluids. These systems use the concept of temperature differentials to achieve thermal capacities. In the design of any such system, the systems engineer should employ the maximum possible temperature differential. As an example, if a system temperature differential of 60 F can be achieved in a heating system, the water flow rates and consequently the pumping horsepower can be reduced to one-third of those for a system design based on a 20 F temperature differential. There are several techniques available for achieving this, among them coils designed for large drops and series connection of loads. Primary-secondary circuits are sometimes required, but the total pumping energy is still reduced.

It is more difficult to achieve larger temperature differentials with chilled water, but consider that a 15 F rise in lieu of 10 F will result in a 33 percent reduction in flows and, consequently, in energy expended for pumping. An additional benefit is usually lower investment cost in pumping and distribution systems.

- *Air system pressures and operating schedules*—Although some control schemes require high air pressures, the use of high-pressure high-velocity air distribution systems should be avoided unless techniques are employed to reduce fan energy consumption at reduced building loads. If a variable volume refinement is not incorporated, fan energy will often exceed the energy requirement of the basic refrigeration machinery because of the greater number of hours of fan operation.

An additional consideration in the selection of fan systems is the building occupancy schedule. The possibility of operating a central fan system a number of hours per year with greatly reduced occupancy rates should be prevented.

- *Primary conversion machinery selection*—Primary energy conversion apparatus such as boilers, chillers, and condensing units should be matched in size modules to the system's part load profile. Each module of machinery should be sized so that it will rarely operate at less than 50 percent of design or rated load. A study of most commercially available energy conversion systems will reveal that the energy input rate (per unit output) increases exponentially as the output decreases. The reason for this is the basic parasitic loading that contributes to mechanical inefficiencies at full load; most of these do not decrease as the output decreases, and with the loss remaining constant, apparatus efficiency decreases.

Capacity reduction modes constitute an additional consideration in the application of refrigeration machinery in smaller (reciprocating) sizes. Analogous to terminal system control, the capacity reduction mode that provides the best or most consistent result is the one that consumes the most energy. Compressor control modes, in order of increasing part load energy consumption, are: on-off, cylinder unloading, hot gas bypass.

- *Refrigeration and boiler system auxiliaries*—Energy consuming auxiliary devices such as condenser water pump motors, cooling tower fan drives, forced draft fan motors, feedwater pump drives, etc., should be scrutinized thoroughly to determine the combination of devices that imposes the lowest power burden on the system and thus results in minimum energy consumption. Cooling tower fan drives can be very low in specific power requirements, but selection without concern for this parameter commonly results in requirements as high as 0.25 kW per ton. In applying condenser water pumps, one must exercise care to arrange the tower, cold water sump, and pump to minimize static lift. In larger systems, multiple cells and variable pumping provide means of optimizing energy use effectiveness.

- *Energy conservation devices*—There are numerous devices and components available that have been specifically developed and marketed to conserve energy. Some examples are heat reclaim wheels, double bundle heat pumps, "heat of light" systems, so-called total energy systems, water source incremental heat pumps, etc. These devices cannot be overlooked in any system design; they must be considered. Unlike the measures recommended in the previous considerations, use of these devices may often penalize investment cost, returning the increment out of operating energy cost savings.

- *Energy source selection*—The selection of an energy source or sources should be made independently of the above considerations. Once specific building energy consumption has been minimized, the source selection is relegated to owning and operating cost economics (present & anticipated) and availability trends.

Suggested checklist

Possibly, the major pitfall of designers has been to initiate an energy economics evaluation with a study for energy source selection, a technique that clearly is analogous to the tail wagging the dog. When the above considerations are applied to the energy economics parameter, power and energy consumption are minimized; and thus the cost will be minimal, regardless of the source. A suggested checklist for energy source selection is:

1) cost;
2) availability;
3) efficiency of conversion, at full and part load;
4) investment cost for storage, handling, and conversion apparatus;
5) environmental requirements of space;
6) environmental requirements of community;
7) demands and consumption of system;
8) availability of apparatus involved and its maintenance and service availability;
9) reliability of source;
10) reliability of conversion apparatus.

Owner's design guidelines

In applying the parameter of energy economics to building systems, the designer must take care not to introduce complexities that cannot be understood by the maintenance and operating staffs. Complete understanding is necessary if the design intent is to be carried out. Many efforts at achieving energy economics without consideration of this point have led to failure of a system to operate efficiently and, in many cases, failure even to satisfy performance requirements. Thus, the designer must always be guided by the rule that simplicity in design will result in successful performance. This consideration certainly affects the specific building energy requirement, and it offers more assurance that design performance will be achieved.

The University of Missouri-Rolla, as a result of the study, developed a set of system design guidelines to be applied to future buildings on campus. Those guidelines involved in energy considerations are:

- Whenever possible, cooling coil capacity control shall be by throttling valve, resulting in load response by variable flow.
- No loads that are humidity-critical, because of process requirements, shall be connected to the building chilled water system. All loads representing normal occupancy or human comfort shall be connected to the chilled water system.
- Special attention shall be given to minimizing all system auxiliary motor loads.
- If the following limitations are exceeded, special permission must be obtained from the University: refrigeration auxiliaries, 0.25 kW per installed ton; system auxiliaries, 0.25 kW per installed ton.
- Every effort shall be made in building and system design to minimize the energy requirements of the environmental systems. A thorough analysis of the energy requirements shall be performed and reviewed with University authorities prior to final design development. Areas of special attention shall include: lighting levels, light switching techniques, ventilation requirements, system selection and control logic, and fenestration.

These design guidelines could be considered a method of energy rationing, but it is hoped that they will simply serve to make design teams conscious of the energy economics parameter.

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