Final Report

on

POWER REDUCTION IN RESIDENTIAL AIR CONDITIONING SYSTEMS THROUGH THE USE OF THERMAL ENERGY STORAGE

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EXECUTIVE SUMMARY

During the past 20 years Texans have come to appreciate and to depend upon the comfort level provided by residential air conditioning. In fact, the air conditioner has become a sort of panacea for the hot and humid weather which covers much of the state for about half of each year. In the early 1950s residential air conditioning was thought of as a luxury option, but now it is considered an essential part of any comfortable home. More than 65% of the state's homes now have some form of air conditioning.

Today a typical Central Texas residential energy bill is about $1,000 per year (electricity and natural gas), and more than $400 of this total results from the use of air conditioning. The impact of the increased air conditioning load upon electric utilities has been equally dramatic. The summer peak demand for electric power continues to grow each year as air conditioning use becomes more widespread in all sectors of our society. Between 20 and 40% of the current summer demand peak in most Texas cities is due solely to the use of residential air conditioning. This trend has forced many utilities to add generation capacity just to meet summer demand peaks. The resulting low load factors and poor utilization of installed capital equipment have contributed to the rapid increase of electric utility rates during the past few years.

One system concept which shows great potential for reducing the summer peak caused by the widespread use of air conditioning is the AC/TES system--air conditioning with thermal energy storage. This type of system acts as a "thermal flywheel" by storing cooling capacity at night and retrieving it during the day.

Application of this concept involves replacing a conventional central unit, typically 3 or 4 tons of condenser capacity, with a smaller condensing unit and an insulated thermal storage tank. The storage unit contains either about 1,500 gallons of water or about 300 gallons of ice and water. During the off-peak hours the excess cooling capacity of the AC/TES system is stored in the thermal storage tank. This excess capacity is later retrieved from the storage unit to handle the next peak heat load, thus allowing the condensing unit to be turned off during the entire electric utility peak demand period. Therefore, the peak power consumption of the AC/TES system occurs at night, and this tends to improve the utilities' load factor. In fact, widespread use of this off-peak cooling concept could easily reduce the peak demand in many Texas cities by 15 or 20%.

This study report explores the dynamics of operation and the economics of two types of AC/TES systems. These are the chilled water system, designated CWS, and the ice storage system, designated ISS. The design methodology for these two concepts is included in sections IV and V of this report. The theoretical performance of these two designs is compared with the performance of a typical central air conditioning unit, designated TCS, in the summary on the following page. All three units are assumed to serve a typical Austin residence with 1,630 square feet of floor space and are subjected to identical design day summer heat loads.

Note in the summary of data that the AC/TES system reduces the peak power requirement by as much as 40% and shifts this demand to off-peak hours. The annual energy consumption for the CWS is 22% less than for the TCS, and this results in an annual savings of $306 in operating costs, assuming time-of-day rates. The corresponding savings in operating costs using current residential rates would be less than $100 annually. Therefore, current rate structures do not offer enough incentive for residential customers to switch to an off-peak cooling system like the CWS or ISS.

However, a progressive rate structure, such as time-of-day pricing with a 200% premium for peak-hours power, would result in a 3- to 4-year payback period for these storage type cooling systems. If utilities and regulatory agencies take the initiative and move toward adopting electrical rates that accurately reflect the true cost of service, particularly during peak consumption hours of each day, AC/TES systems will become economically attractive.

SUMMARY OF PERFORMANCE AND ECONOMIC FACTORS FOR AC/TES SYSTEMS

Peak Annual Power Requirement

TCS - 5.41 kilowatts, peak
AC/TES
CWS - 3.23 kilowatts, off-peak
ISS - 3.38 kilowatts, off-peak

Annual Energy for Air Conditioning

TCS - 8321 kilowatt-hours
AC/TES
CWS - 6478 kilowatt-hours
ISS - 6581 kilowatt-hours

Annual Cost of Operation

(Assuming Proposed Time-of-day Rates)

TCS - $557
AC/TES
CWS - $251
ISS - $261

Savings
$306

Time to recover the incremental investment in an AC/TES system:

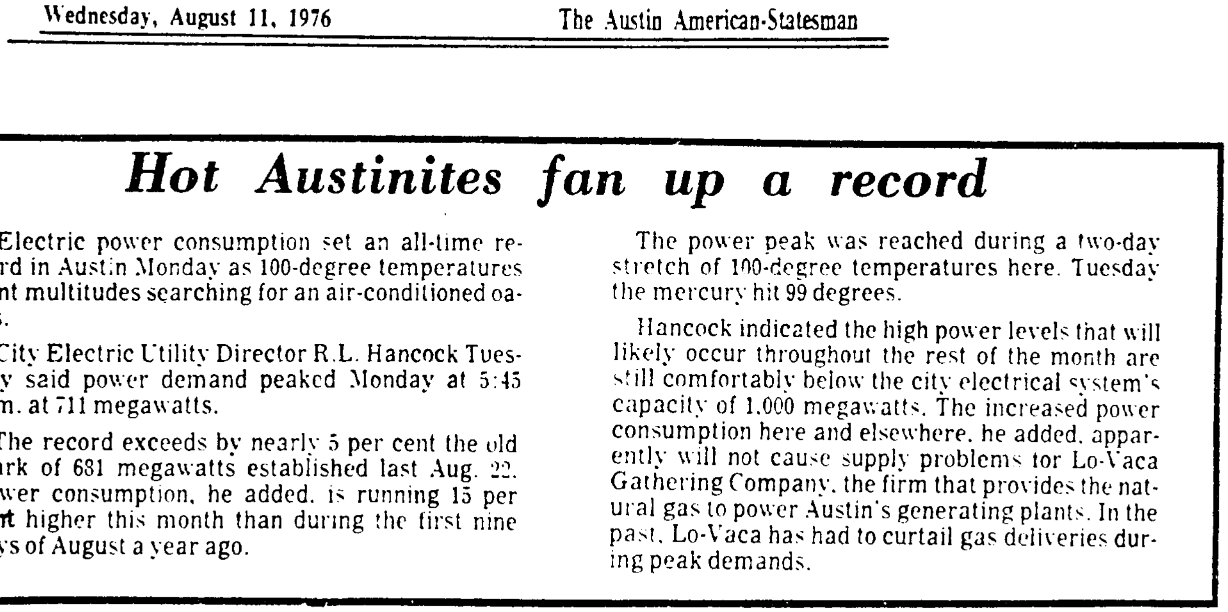
3 or 4 years

I. INTRODUCTION

A. The Demand Peak Problem in Texas Cities

During 1974, residential use of electric power in Texas accounted for approximately 31% of all electrical energy distributed within the state. Although the residential percentage of total consumption has increased only slightly over the past 10 years, the consumption per customer has approximately doubled during that same time period. For example, in 1964 the average Texas residential customer used about 5,100 kwh per year. By 1974 the average use had risen to about 10,000 kwh per year. This increase is primarily a result of the extensive use of electrical appliances and equipment in the home today. In addition, a greater percentage of homes are now equipped with central air conditioning, and an increasing number of homes have electric furnaces for space heating. Census data from 1970 indicate that about half of the new homes built that year used a central air conditioning system. This percentage has increased further in the past 6 years.

The continued growth of electrical demand has provided persistent pressure on Texas utilities to increase their generating capacity. In recent years the cost of increased capacity has risen dramatically to values as high as $600/kw. Much of this new capacity in the state has been installed to meet peak power requirements which occur during the summer months. The imbalance between summer and winter power loads has resulted in relatively poor utilization of the total system capital investment, and this in turn has contributed to today's higher rates for all utility customers. Figure 1 illustrates the summer peaking effect for three electric utilites in Texas. Note that in each case the August 1976 peak demand is greater than the 1975 peak, and that the 1976 data represent new record peaks for all three utilities. These peaks can be correlated directly to the widespread use of electric air conditioning systems by all classes of customers served by these utilities. In fact, for many cities across the southwest region of the United States the use of residential air conditioning contributes the largest single component of load to the summer demand peak. As evidence of this fact, consider the following article which recently appeared in an Austin newspaper:



Wednesday, August 11, 1976 The Austin American-Statesman

Hot Austinites fan up a record

Electric power consumption set an all-time record in Austin Monday as 100-degree temperatures sent multitudes searching for an air-conditioned oasis.

City Electric Utility Director R.L. Hancock Tuesday said power demand peaked Monday at 5:45 p.m. at 711 megawatts.

The record exceeds by nearly 5 per cent the old mark of 681 megawatts established last Aug. 22. Power consumption, he added, is running 15 per cent higher this month than during the first nine days of August a year ago.

The power peak was reached during a two-day stretch of 100-degree temperatures here. Tuesday the mercury hit 99 degrees.

Hancock indicated the high power levels that will likely occur throughout the rest of the month are still comfortably below the city electrical system's capacity of 1,000 megawatts. The increased power consumption here and elsewhere, he added, apparently will not cause supply problems for Lo-Vaca Gathering Company, the firm that provides the natural gas to power Austin's generating plants. In the past, Lo-Vaca has had to curtail gas deliveries during peak demands.

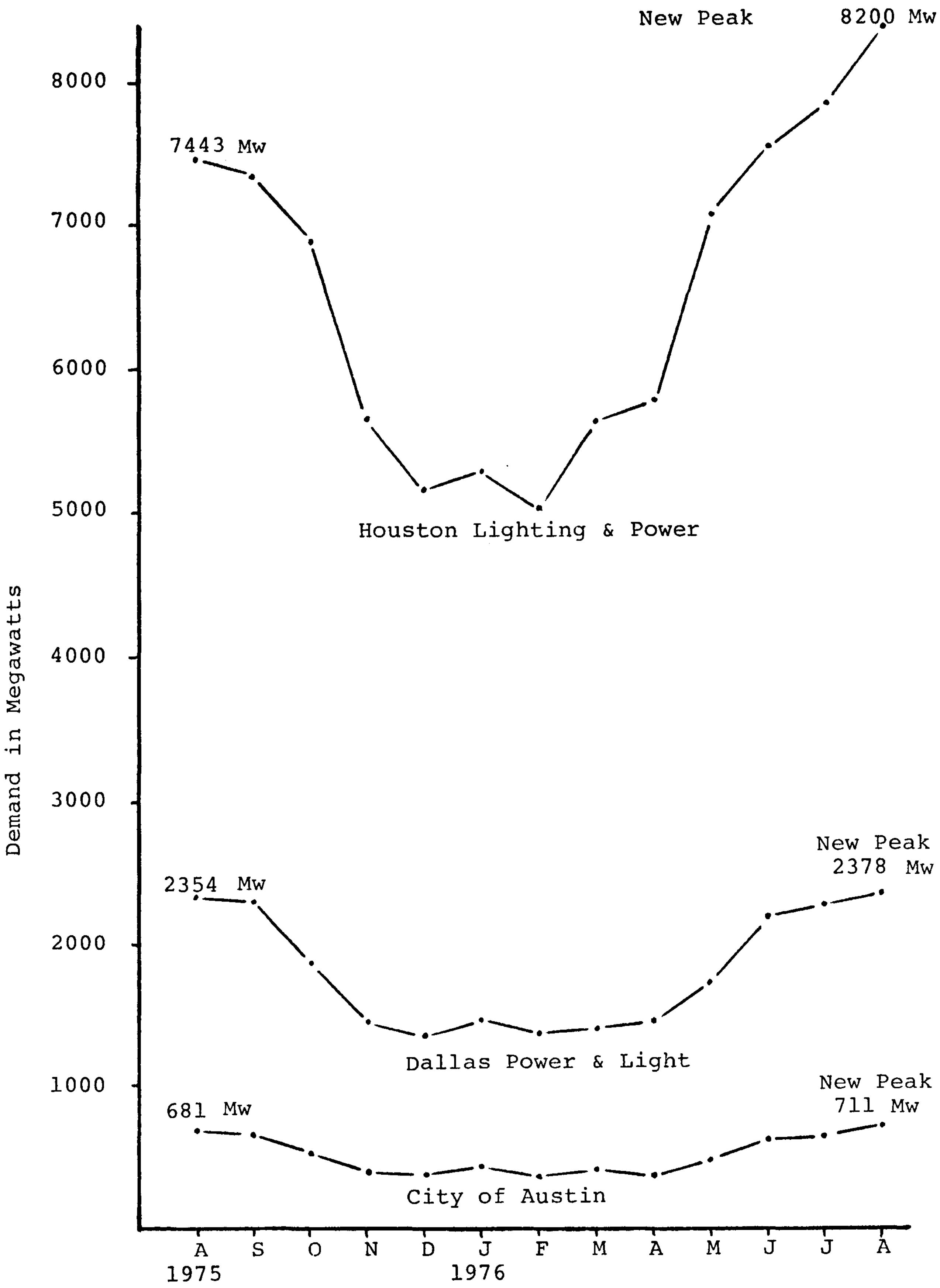


Figure 1

DEMAND PROFILES FOR TEXAS CITIES

Austin's electric utility now estimates that 280 megawatts of its August 1976 peak, or about 40% of the peak, were due to the use of residential cooling systems. Similarly, Dallas Power and Light estimates its residential air conditioning fraction at about 31% of peak demand, and Houston Lighting and Power estimates its fraction at 27%. Since air conditioning represents the largest single consumer of electrical energy in the residential sector, it should become a prime target for load management and energy conservation. One promising concept for "shaving the peak" off the daily demand curve is to operate a residential air conditioning system during off-peak hours and store the excess cooling in a thermal storage unit for use during the peak hours. This concept, known as air conditioning with thermal energy storage (AC/TES), is the subject of this report.

In the initial stages of the AC/TES project, the potential for year-round thermal storage in homes using a heat pump was considered. However, after some study of the technical factors involved in designing storage for both heating and cooling, and considering the current predominance of gas heating, it was decided to focus this study on system dynamics and economics of "cooling-only" systems with storage. In the heating mode heat pumps offer significant economies when compared to resistance heating. However, in the relatively mild winter climate of Central Texas, the addition of thermal storage to the heating cycle of a heat pump is of secondary importance when compared to the potential of a pure cooling system with thermal storage.

B. Residential Energy Requirements

A detailed energy analysis of a typical Austin residence was recently conducted by Jones and Hendrix [11].* This study evaluates the effectiveness of various energy conservation options for a typical house with 1,600 square feet of floor space. Both all-electric and gas/electric home designs were evaluated. The annual energy requirements determined in this study for the more common gas heating and electric cooling combination are shown in the upper part of figure 2. This pie chart illustrates that of the five major components of total annual primary energy for the typical home, air conditioning's energy fraction of 36% is by far the largest. In the lower chart of figure 2 these energy components have been converted into cost components using recent average utility rates of 5¢/kwh for electricity and $2.78 per million Btu for natural gas. Note that the cost of air conditioning, at $416.00, represents 42% of the total annual energy bill for a typical Austin residence.

The energy consumption data for the air conditioner in the Jones-Hendrix study were based on computer-generated heat load profiles for the typical residence. These profiles represent the summation of heat loads due to people, appliances, equipment, and the external environment, so that the annual energy requirement for air conditioning could be determined. A

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*All references are listed in section VIII of this report.

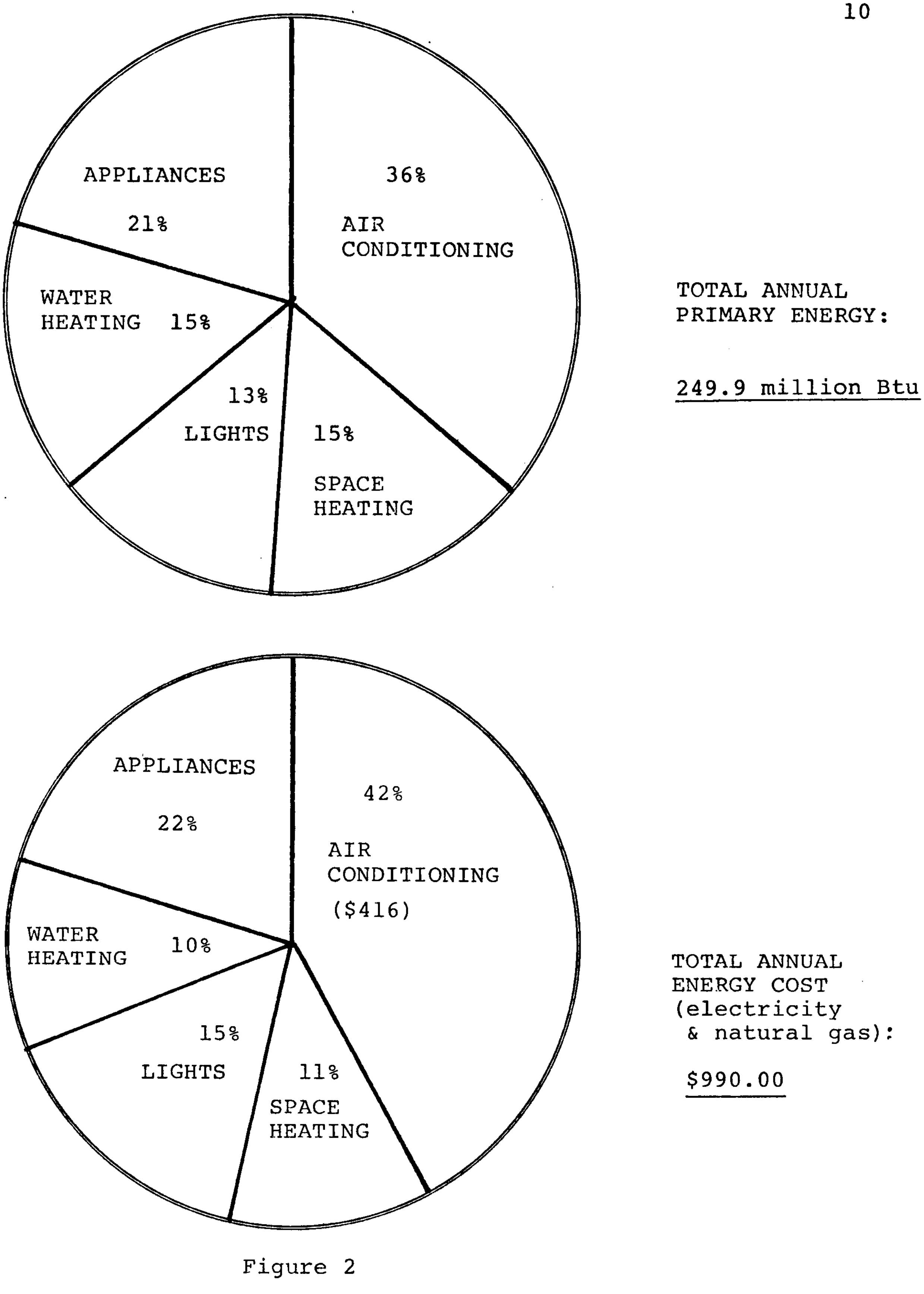


Figure 2

ANNUAL RESIDENTIAL ENERGY CONSUMPTION AND COST
(TYPICAL AUSTIN HOME WITH GAS HEAT/ELECTRIC COOLING)

detailed description of the typical home, the computer analysis, and supporting information are presented in reference 11. The weather input data used for the computer analysis in the referenced report are actual data obtained from the Austin national weather bureau. The calculation procedures used in this report took into account occupancy, lighting and appliance loads, the thermal capacitance of the house, and the variations in thermal and solar loads. Both latent and sensible heat loads were calculated so that the operating characteristics of the cooling coil for both cooling and dehumidification could be determined.

Also from reference 11 and of particular interest to the thermal storage project were the heat load characteristics for the maximum load day of the year. The worst-case data are normally used to size an air conditioning system. These data are shown in table 1 and indicate a maximum load of 2.67 tons between 5 and 6 PM on the maximum load day for the typical residence. This same table of data is used later in this report to determine the performance and economics of a typical central system and two off-peak air conditioning systems with thermal storage.

C. Financial Incentives for Reducing Peak Demand

1. New rate philosophies

During the past three years the electric utility companies in Texas, their customers, and local regulatory agencies have spent considerable time and effort in the search for more

Table 1

HEAT LOAD CHARACTERISTICS OF TYPICAL AUSTIN RESIDENCE
(Maximum Load Day of the Year)

Time	Ambient Dry Bulb Temp., °F	Heat Loads - Btu Latent Load	Sensible Load	Total Load	Total Tons
12 PM - 1 AM	84.0	4215	5172	9387	0.78
1 - 2	82.0	4322	4174	8496	0.71
2 - 3	80.0	4861	3240	8101	0.68
3 - 4	79.0	4559	2573	7132	0.59
4 - 5	78.0	4623	2047	6670	0.56
5 - 6 AM	78.0	3894	4058	7952	0.66
6 - 7	77.0	3929	6572	10501	0.87
7 - 8	77.0	3615	5301	8916	0.74
8 - 9	80.0	4165	9502	13667	1.14
9 - 10	82.0	3750	11775	15525	1.29
10 - 11	85.0	3417	13719	17136	1.43
11 - 12 NOON	88.0	2829	14685	17514	1.46
12 - 1 PM	92.0	2837	15251	18088	1.51
1 - 2	95.0	2553	16937	19490	1.62
2 - 3	98.0	2618	18954	21572	1.80
3 - 4	100.0	2948	22159	25107	2.09
4 - 5	99.0	2581	27717	30298	2.52
5 - 6 PM	98.0	2657	29411	32068	2.67
6 - 7	97.0	2444	25937	28381	2.37
7 - 8	95.0	2415	16327	18742	1.56
8 - 9	92.0	3278	14335	17613	1.47
9 - 10	90.0	3054	12315	15369	1.28
10 - 11	88.0	3411	10347	13758	1.15
11 - 12 PM	87.0	3674	6299	9973	0.83

TOTAL DAILY LOAD = 31.78 ton-hr

TOTAL ANNUAL COOLING LOAD = 45.7 million Btu

Source: Reference 11

realistic methods of pricing electric power than the traditional "declining block rate" method. These studies of electric rate structures have resulted in proposals that cover a wide spectrum of philosophies. For example, some rate proposals have included "life-line," "inverted," or "flat" rate features that tend to reduce the cost per kilowatt of electric power for the small consumer. These rate structures are usually based on social objectives and tend to shift the financial burden to large consumers. They also ignore economies of scale associated with fuel, generation, and distribution costs.

At the other end of the spectrum, the more conservative rate proposals have attempted to distribute all elements of power generation costs more accurately by using what is commonly referred to as the "cost of service" philosophy. In spite of widely varying approaches to rate design, two rate design factors are generally agreed upon: (1) the rate structure should encourage energy conservation, and (2) the rate structure should charge a higher unit cost during peak demand periods so as to encourage a shift of kilowatt demand to off-peak hours.

One pricing structure for electrical energy that seems destined for wide adoption in the future is the concept of "time-of-day" pricing. This is one type of peak-load pricing. This pricing method creates higher rates, perhaps 3 or 4 times higher, for electric energy delivered during peak hours.

Time-of-day pricing acts as a strong financial incentive for customers to shift electrical loads to off-peak hours. Unfortunately, the ability of a typical homeowner to shift his peak load is severely limited in the case of conventional air conditioning units. The typical residential customer can only respond to time-of-day pricing by performing other tasks, such as cooking and clothes washing or drying, during off-peak hours. Any attempt to shift air conditioning load by raising thermostat settings above the 78°F to 80°F range, or by periodically turning the system off, will severely reduce the comfort level of the residence.

The concept described in this report, namely air conditioning with thermal energy storage, offers the possibility of shifting the major component of residential power demand to the off-peak period while maintaining normal comfort levels in the home during the peak period. If successfully implemented, this cooling concept would allow a residential customer to respond to time-of-day rates and, at the same time, save both money and energy.

Since the assumed rate structure has a strong influence upon operating cost of any air conditioning system, analyses in this report consider both a current residential rate (RS rate) and one possible time-of-day rate (TD rate).

2. Problems with Demand Metering

As previously mentioned, one of the motives for revising rate structures has been to discourage peak consumption of power and thereby improve the load factor of electric utilites. The "charge for demand" feature does exist in most of today's rate structures, but only for large energy customers where the cost of a demand meter can be justified. Rate structures for small commercial and residential customers usually have no provision to charge for kilowatt demand peaks during the billing period, because it is considered uneconomical to install individual demand meters for many small customers. In fact, the lack of a low-cost meter which combines both energy and peak-demand metering functions seems to be the major obstacle in switching to time-of-day rate structures.

When one considers the advanced state of the art in today's microelectronic devices, such as calculators, LED watches, and microcomputers, it seems reasonable to assume that the electronics industry could produce a solid-state combination energy and demand meter for less than the cost of the old-style kilowatt-hour meter. However, none of the meter manufacturers has taken the initiative to develop low cost demand meters or combination demand/energy meters. The reason is an apparent stalemate between the meter manufacturers and the regulatory agencies. The manufacturers seem to be waiting for the agencies to adopt time-of-day rates, and the agencies seem to be waiting for the manufacturers to develop and manufacture low-cost demand meters. These problems with demand metering may be overcome in the near future, and if they are, the door will be opened for adoption of time-of-day rates on a broad scale.

3. Proposed Time-of-day Rate for Austin

One major objective of this program has been to evaluate the economics of operation for an off-peak cooling system, using a time-of-day rate structure. Since time-of-day rates do not currently exist in any Texas cities, it has been necessary to develop a hypothetical, yet realistic, rate structure for the economic evaluation.

The basic assumption in developing the proposed time-of-day rate for Austin is that it should generate approximately the same revenue as the current residential rate. The current RS rate generates about $1.20 in revenue per day per kilowatt (24 kwh), so the effective unit cost, including fuel cost adjustment, is about $0.05/kwh. Next, consider the 1975 maximum load profile for the Austin electric utility shown in figure 3. Note that approximately 40% of the peak value of 681 Mw is due to residential air conditioning.

Since the system peaks in the late afternoon during the summer, it is desirable to select the 7 hours around the 4:30 PM peak, from 1:00 PM to 8:00 PM, for the peak-price period. The proposed time-of-day rate shown in figure 3 assigns a 200% surcharge (three times the base rate) for kilowatt-hours consumed during the peak period. The revenue generated by this rate will be approximately the same as the current RS rate if we assumed a 20% demand elasticity during peak hours and a 5% increase in demand during off-peak hours due to load shifting. This rate structure, which consists of

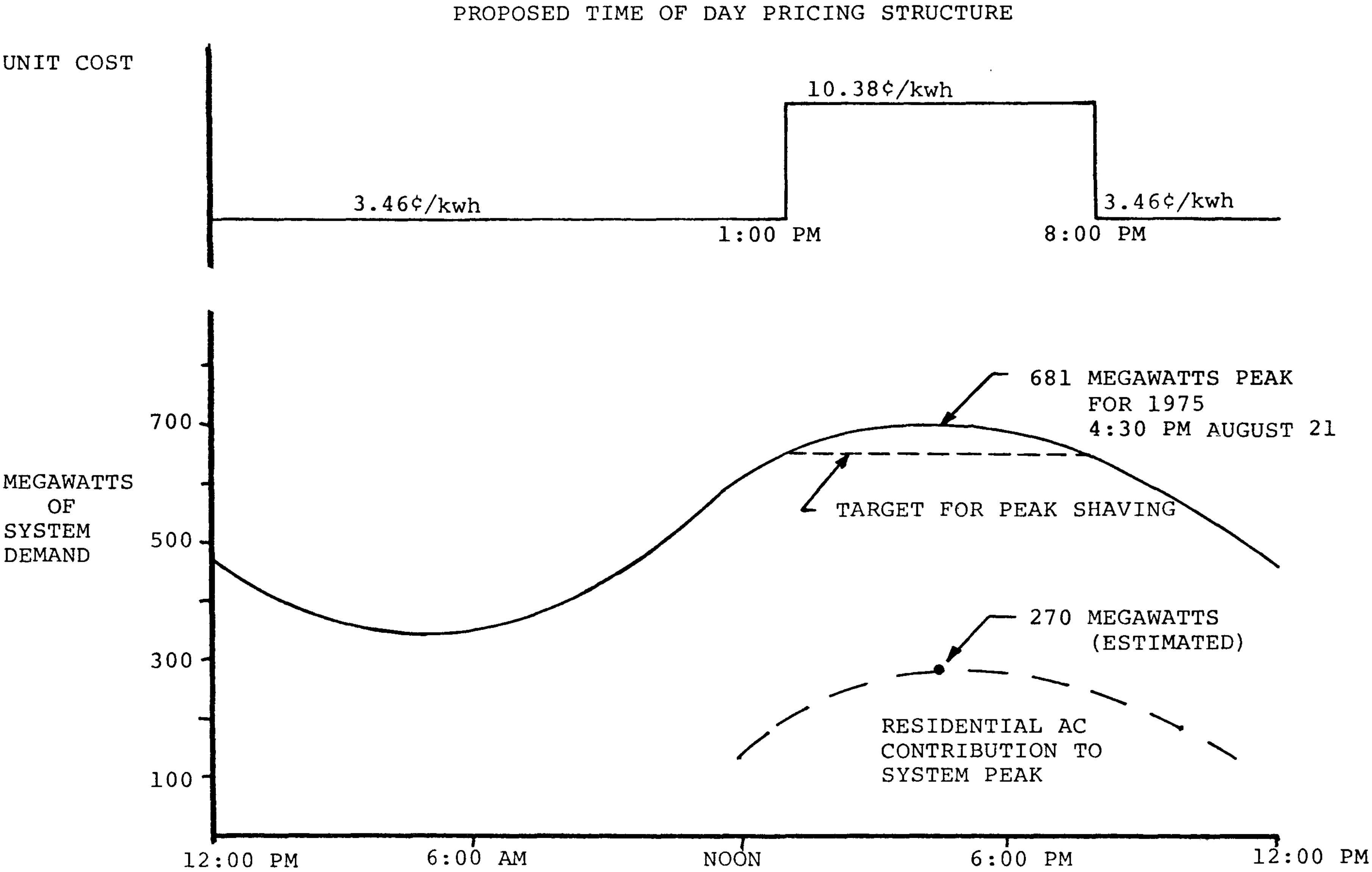


Figure 3

AUSTIN ELECTRIC UTILITY DEMAND PROFILE

a charge of 3.48¢/kwh for the off-peak energy and 10.38¢/kwh for peak energy, is used to evaluate three air conditioning system concepts in the following sections.

II. LITERATURE SURVEY ON STORED COOLING TECHNIQUES

An abundance of government-funded research has been carried out in the past 5 years on the techniques for storing thermal energy. Much of the R&D has focused upon the unique physical properties of storage materials or the importance of storage concepts as an integral part of a solar heating and cooling systems. This study recognizes the importance of these areas; however, this survey focuses on those recent activities which are more directly related to off-peak storage of cooling for residential air conditioning. The following paragraphs are brief summaries of the 11 most pertinent research works in the field of thermal energy storage. A complete listing of all references is given in section VIII, at the end of this report.

Faced with high demand during the system's peak load period and determining that it was mainly due to air conditioning, Wisconsin Electric Utility began studying time-of-use rates as a means of reducing this high peak load. After some investigation, they decided that development of a simple and economical residential ice bank system to store cooling during off-peak hours would be feasible. "Keep Your Cool" by J. McLean and R. Krubsack [1] is an article based on these studies. Their first system used a 180-gallon water tank with 200 feet of coiled copper tubing and an expansion valve to act as a combination ice bank/evaporator. This unit was connected to a standard-sized condensing unit.

Next, a conventional cooling coil was connected into a water coil, and a blower was added. A chilled water loop and a pump for circulation were used to tie the fan/coil unit to the ice bank. A temperature-sensitive device was used to control the ice build-up on the coil. The system operated successfully, providing the water coil with contant 32°F ice water. Subsequently, the A. O. Smith Co. was contracted to build a few improved evaporator/storage tanks for further demonstration projects. They produced a tank similar to a domestic water heater with 9 ton-hours of cooling capacity. Of these 9 ton-hours, 7½ ton-hours were due to the 630 pounds of ice and 1½ ton-hours were due to the water's going from 35°F to 55°F. This article suggests that a 25% reduction in water chilling condenser capacity should be assumed when freezing ice in a tank of this design because of the lower suction pressure. This scheme was judged to be uneconomical unless a price difference was created between peak and off-peak rates.

<u>Preliminary Survey of Electric Utility Solar Projects</u> [2] is important as a source of information about utility interest in thermal storage projects. Of the 135 utilities surveyed, most of which were major municipal utilities, 53 responded. Of particular interest in this report are those projects that utilize thermal energy storage to reduce daily peak-period demand. Two categories were surveyed: those projects that were in progress and those that were planned.

Nineteen percent of the utilities were actively involved in projects studying or demonstrating residential TES. Eleven percent had plans to start such projects in the near future.

In early 1971, the University of Pennsylvania began a 3-year NSF-sponsored project to study and demonstrate the use of thermal storage to conserve and better utilize electric power. The main areas of study were off-peak air conditioning, residential heating with solar energy, and materials for thermal energy storage. Conservation and Better Utilization of Electric Power by Means of Thermal Energy Storage and Solar Heating [3] reports that two types of off-peak air conditioning systems have been developed and demonstrated. One is a novel recondenser air conditioning system. The other system uses a salt-hydrate material, with its phase change advantages, as the storage medium. Cooling capacity is stored by blowing cold air across banks of this material in the off-peak period; later this cooling capacity is retrieved to aid the conventional air conditioning system in meeting the peak load. Cooling performance has been found to be unstable because of the large decrease in cooling capacity as the salt-hydrate melts. The project's study of TES materials examined various latent storage materials and their performance for 24-hour freezing-thawing cycling, such as would be necessary in a typical thermal energy storage system. The conclusion of this study is that organic waxes offer the most promise for the near future.

Recondenser Off-Peak Air Conditioning System: Design and Operation by J. C. Dudley [4] explains in detail the design and operation of the University of Pennsylvania's recondenser off-peak air conditioning system. It is basically a standard vapor compression air conditioning system with the exception that it has two evaporators with a second refrigerant condenser in between. The return air is precooled as it passes over the first evaporator and then dehumidified and cooled further by the second evaporator. This second condenser, or the "recondenser," is a water-cooled condenser using cold water pumped from a water storage tank. The cold water storage is built up during the off-peak period by a bypass arrangement that allows refrigerant to flow directly to the recondenser and chill the water pumped from storage. The system cycles between thermal storage and the space load during the off-peak period. During the peak period it cools only the space load with a boost from the storage tank. This system concept allows a smaller condensing unit to be used since it runs more continuously than a conventional unit. In addition, it has a better efficiency as a result of the novel recondenser application. This system produces a 6% energy savings compared with a conventional system, and it reduces the peak power requirements by approximately 50%.

The Annual Cycle Energy System (ACES) operates by forming ice during the winter as a result of heat pumping from a water tank for space and water heating. The system then reverses and uses the stored cooling for "free" summer air conditioning. The most important point in the article, entitled "Ice and Water: Annual Cycle Energy System Offers Savings in Heating, Cooling," by H. Fischer [5] is that geographic location is critical to balanced operation; that is, the winter space and water heating loads must approximately equal the summer cooling load for the concept to work efficiently. According to the article, the northern limits of ACES territory would be the latitude of Minneapolis and the southern limits around the latitude of Atlanta. Therefore, much of Texas and other southern states would be out of ACES territory. At the optimum location, with balanced seasonal loads, it is estimated that ACES could save up to 77% of the annual energy required by conventional heating and cooling systems.

"Sizing and Application of Thermal Storage Systems," by E. L. Cuplinskas [6], illustrates how thermal storage can reduce a cooling system's required capacity to a value equal to the average daily cooling load for the peak load day. The same approach could be used for the heating mode during the winter. Energy savings would be realized as a result of longer nighttime chilling operation during the cooling season. It is pointed out that sizing of thermal storage is done most accurately by computer simulation. This article considers commercial applications, but the same design principles would hold for residential systems. The water storage tanks described in this article are segmented so as to minimize the irreversibilities associated with mixing cold supply water and the warmer return water.

"A Simplified Heating-Cooling Thermal Storage System," by E. L. Cuplinskas [7], considers a basic problem in applying year-round storage systems to residential or small commercial applications. That problem is the relatively high costs for controls and piping for a storage system. These costs can usually be justified on large buildings where energy savings are large and the cost fraction of peripheral equipment is small. However, these costs may not be justifiable on a small building or residence. The author points out a need to simplify storage systems for smaller users; he proceeds to show that a storage system sized to average out the summer cooling capacity requirements would be adequate for the winter heating storage. Such a system has the potential to reduce the cost fraction of piping and controls. The author points out in the summary that utilities may provide rate incentives for storage systems because storage systems will contribute to reducing summer power peaks.

Proceedings of the Workshop on Solar Energy Storage Subsystems for the Heating and Cooling of Buildings, an NSF/ERDA-sponsored workshop [8], reports on the state of the art of various storage subsystems. Storage schemes are described which use phase change materials and more conventional substances such as water and rocks. Topics discussed include storage structures, insulation, and costs. The section that considers water tank stratification concludes that stratification is desirable for solar hot water storage since it improves the solar system's performance. Other sections of this report indicate that phase change materials are a promising area because storage volume reductions and better material performance are likely to be achieved in the future. In general, this report is one of the most comprehensive and definitive works available today on energy storage systems.

One method to reduce system peak loads is the use of cooling-demand controls. "Cooling-Demand Controls Look Good," a recent article in Electrical World [9], discusses two types of cooling-demand controls. One type uses radio-controlled equipment to turn off the air conditioner compressor for a portion of each hour during the peak period. The other uses a thermostat and timer on the unit to turn off the compressor for a preset amount of time during a period when ambient temperature is above a fixed level, say 90°F. These controls are aimed at shifting use to avoid coincident loads. Several utilities have performed tests on these devices and have found that with appropriate monetary incentives, customers are generally in favor of their use. In addition, peak period load factors were significantly increased for the test installations. Those utilites involved were optimistic about sizeable summer load factor increases if these devices came into widespread use.

"Utility Rate Studies Threaten Whole Concept of Summer Comfort" [10] appeared in a leading HVAC trade publication and describes the dilemma that utilities and homeowners are facing today regarding the cost of energy for comfort. The rate options now under study by various regulatory agencies are described. The article notes that time-of-day metering might be of great benefit to utilities and to the HVAC industry, but its optimum use implies thermal storage--and at this time thermal storage systems are almost nonexistent. It concludes by saying time-of-year prices are a real threat to summer comfort because it is far more difficult and expensive to store cooling for a season than it is to store cooling on a daily cycle.

III. ANALYSIS OF A TYPICAL CENTRAL SYSTEM

At the beginning of this study it was decided that the evaluation of various off-peak cooling systems should be done on a comparative basis. The basis selected for comparing operational power and cost factors was a fairly typical central air conditioning system, one that had adequate capacity to handle the cooling loads defined for the "typical" Austin residence of 1,630 square feet described in table 1.

The key parameters from this table indicate that the typical home requires a maximum cooling capacity of 2.56 tons at about 5:30 PM with a corresponding ambient temperature of 98°F. The normal procedure for selecting a residential system was followed, that is, a combination condensing unit (outdoor) and evaporator coil/blower (indoor) was sized to have a small excess capacity under maximum load conditions for the entire cooling season.

The central system selected as the baseline for comparison with off-peak designs is a nominal 3-ton unit manufactured by Friedrich Air Conditioning and Refrigeration Company of San Antonio, Texas. This system consists of a type CU371 condenser and a type BE49 evaporator coil. The load characteristics and power requirements for this split system are plotted in figure 4 as a function of ambient temperature. From these data the energy efficiency ration (EER) for this system at 95°F ambient temperature can be evaluated as

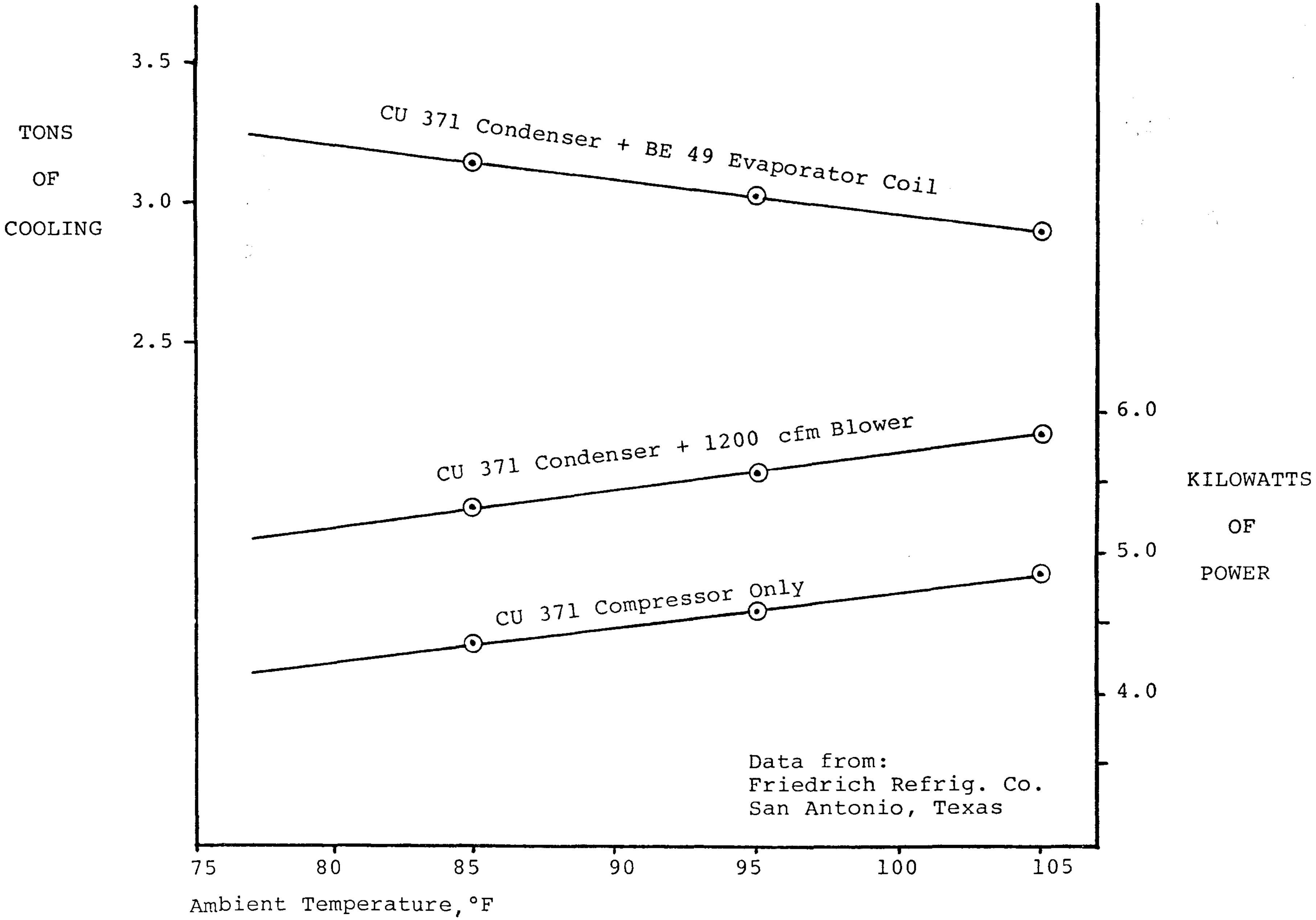


Figure 4

LOAD CHARACTERISTICS - TYPICAL CENTRAL SYSTEM

6.5 Btu/hr-watt. This efficiency is a typical value for central air conditioning systems installed during the past 5 to 8 years, but is less than the newer "high efficiency" central units offered during the last few years by Friederich and other leading manufacturers.

An hour-by-hour analysis of the CU371/BE49 system operating under the design day load data from table 1 is shown in table 2. The system load data in this table include not only the latent and sensible loads from the residence, but also the load due to the blower fan required to distribute cool air at a rate of 1200 cfm.

The system load data (column 3) are converted to kilowatt hours of energy (column 4) using the load characteristic data from figure 4. The hourly cost of operation is then computed using the proposed time-of-day rate from section I. C. of this report. For the entire 24-hour period of the design day the cost of operation is shown to be $4.2872 using the time-of-day rate.

If the residential rate (RS) of 5¢/kwh is applied, the operating cost for the same day is $3.2005. These cost figures now become a basis for comparison with operating costs for the two off-peak cooling systems described in the following sections.

Table 2

ANALYSIS OF TYPICAL CENTRAL SYSTEM

MODE: CM (Continuous)
RATE: TIME OF DAY

Hour Ending	Ambient Dry Bulb Temp., (°F)	System Load (Tons)	Total Kilo-watt hours	Rate ¢/kwh	Total Cost ¢
1	84	.95	1.60	3.46	5.54
2	82	.88	1.46	3.46	5.05
3	80	.85	1.42	3.46	4.91
4	79	.76	1.23	3.46	4.26
5	78	.73	1.16	3.46	4.01
6	78	.83	1.32	3.46	4.57
7	77	1.08	1.71	3.46	5.92
8	77	.91	1.44	3.46	4.98
9	80	1.31	2.14	3.46	7.40
10	82	1.46	2.42	3.46	8.37
11	85	1.60	2.72	3.46	9.41
12	88	1.63	2.85	3.46	9.86
13	92	1.68	3.03	3.46	10.48
14	95	1.79	3.31	10.38	34.36
15	98	1.97	3.74	10.38	38.82
16	100	2.26	4.35	10.38	45.15
17	99	2.69	5.14	10.38	53.35
18	98	2.84	5.41	10.38	56.16
19	97	2.54	4.80	10.38	49.82
20	95	1.73	3.20	10.38	33.22
21	92	1.64	2.96	3.46	10.24
22	90	1.45	2.57	3.46	8.89
23	88	1.32	2.30	3.46	7.96
24	87	1.00	1.73	3.46	5.99
	TOTALS		64.01 kwh		428.72¢

Total Cost at RS Rate of 5¢/kwh = 320.05¢

IV. CHILLED WATER STORAGE SYSTEM ANALYSIS

A. System Description

Various system configurations were evaluated during the study phase of this program, and the chilled water storage configuration which showed the greatest promise was examined in considerable detail. The concept is shown in figure 5. It was chosen for its simplicity, its use of off-the-shelf components, and its potential for low first cost if the system were mass-produced.

The heart of this system is a combination 2½-ton condenser and water chiller which provides sufficient capacity to cool the typical Austin residence as defined in section I. B. of this report. The load characteristics of three particular chilled water condensing units are shown in figure 6. These units are manufactured by Dunham Bush, Inc.; AIPC-2 and AIPC-3 represent nominal 2- and 3-ton units, respectively. Design optimization and sizing of a CWS unit for the typical Austin residence indicated that an in-between-sized unit would be required, so the load characteristics for an AIPC-2½ were developed. These data are plotted as dashed lines in figure 6 and indicate the cooling capacity and power requirements for the 2½-ton unit as a function of ambient temperature. The top curve of the four power curves represents the total system power requirement and includes pump and blower power.

As indicated in figure 5, the flow rate to the supply water storage tank is regulated by a sensor in the tank so that the

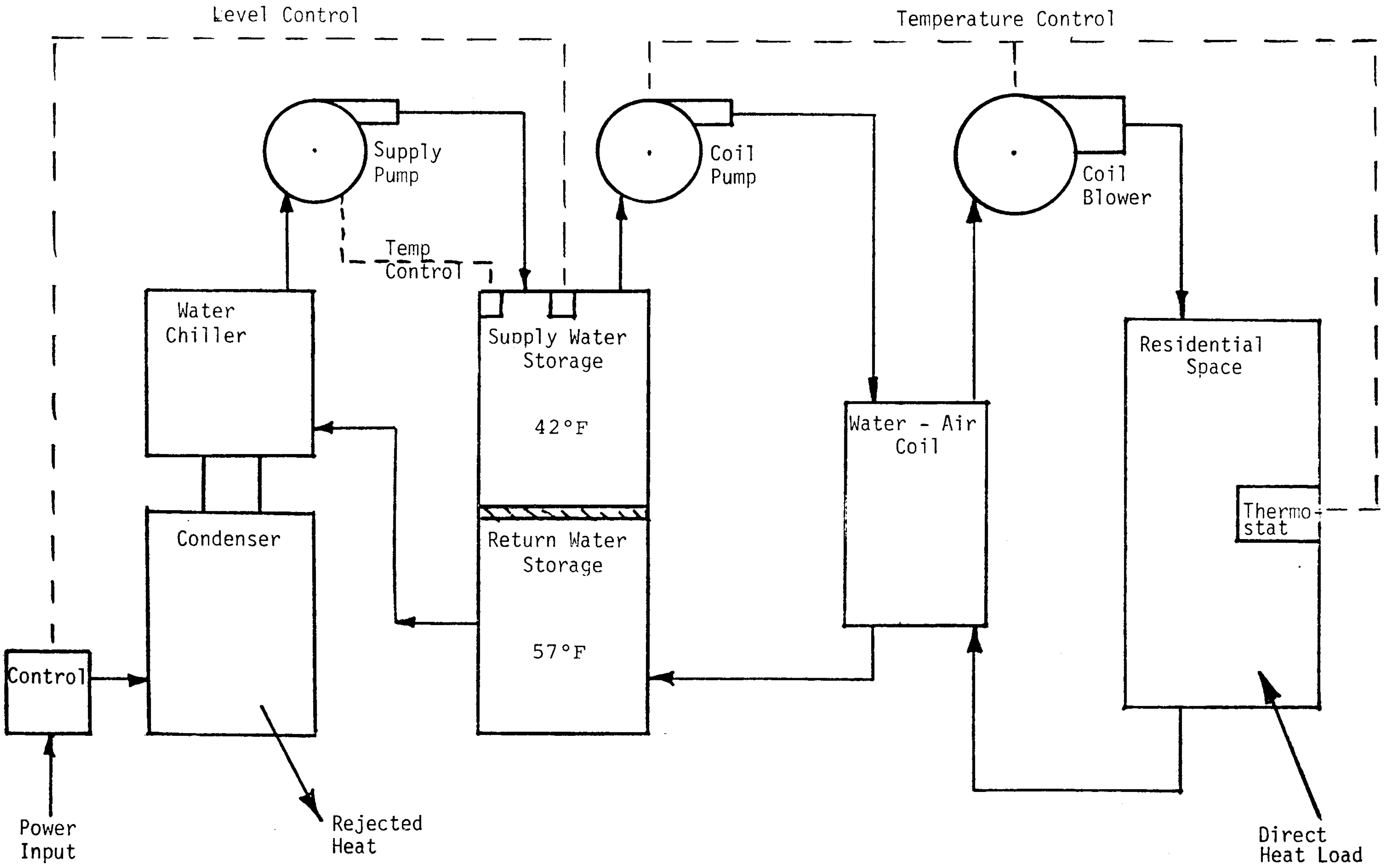
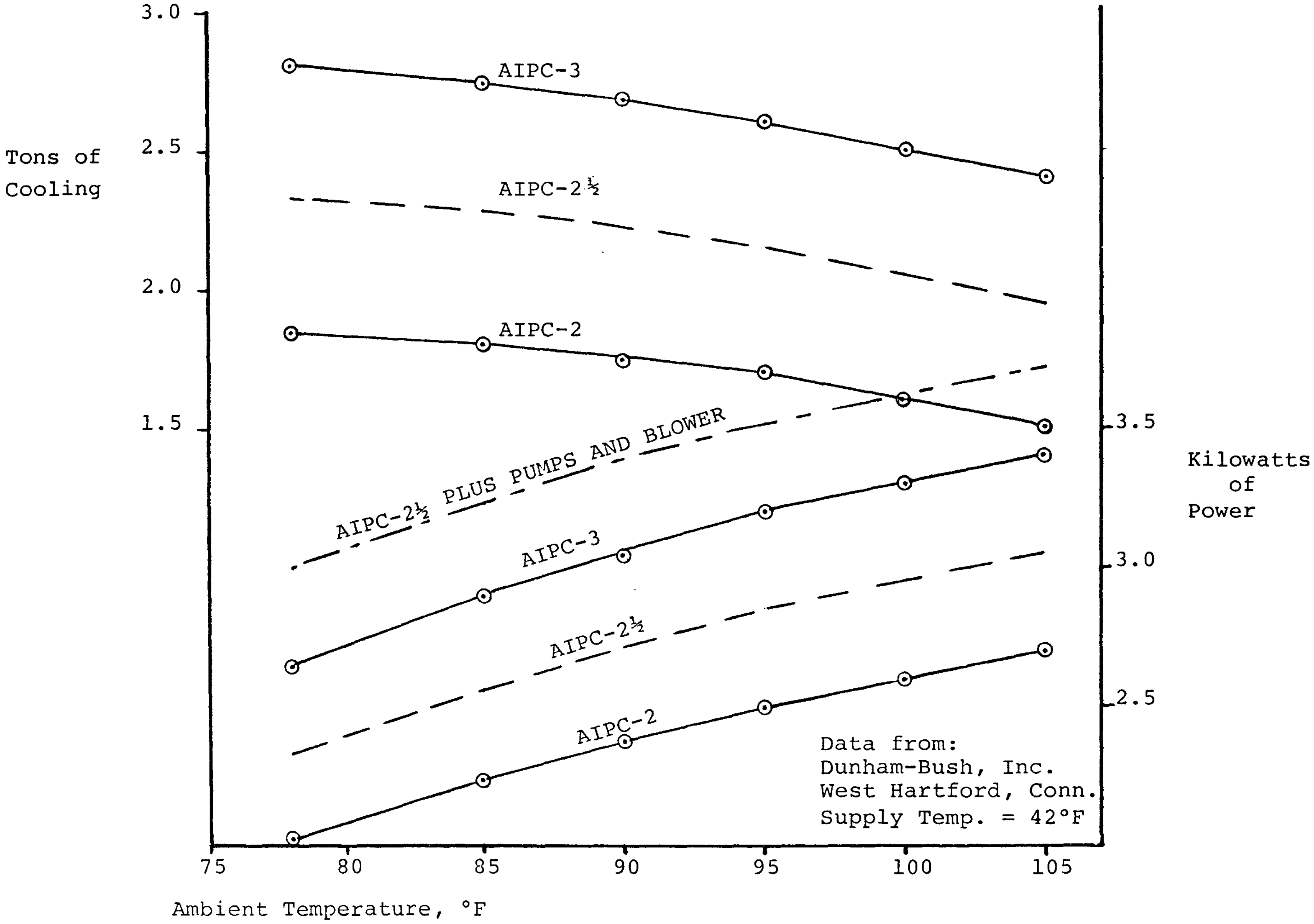


Figure 5

CHILLED WATER STORAGE SYSTEM DIAGRAM



Data from:
Dunham-Bush, Inc.
West Hartford, Conn.
Supply Temp. = 42°F

Figure 6

LOAD CHARACTERISTICS - CHILLED WATER SYSTEM supply temperature remains at approximately 42°F. The tank also contains a level sensor to turn off the condensing unit when the tank is full. Supply water is drawn from storage by a second 5-gpm pump, passed through a water-air coil, and then returned to the other section of the storage tank.

The proposed concept for the 1500-gallon insulated storage tank employs a movable insulated partition to isolate return water from supply water. By preventing mixing of the two water streams in the storage tank, the condensing unit operates at maximum efficiency and the coolant flow rate is minimized. A tank of this type is apparently not commercially available at this time; however, the simplicity of the insulated partition mechanism indicates that such a unit could be mass-produced with only a small investment in development and testing.

In this design a standard 1200-cfm water-air coil unit and blower are used to exchange heat between the residential space and the chilled water from storage. The conditioned space thermostat provides load-proportional flow rates from the supply water pump and coil blower, resulting in a relatively constant return water temperature of 57°F. The sequence of operation of the various components of the CWS system is explained in a following section on system dynamics.

B. <u>System Losses and Storage Requirements</u>

Basic storage requirements can be determined by examining the heat load data in table 1 for the 7 peak hours between 1:00 PM and 8:00 PM. The total cooling requirement during this time interval is 14.63 ton-hours; however, it is necessary to add additional capacity to handle various system heat loads. These loads include heat gain through the storage tank wall and piping insulation, and heat generated in fluid streams due to work being done by two pumps and the coil blower. Assuming the tank is insulated by 8-inch thick, low-density polyurethane, the average tank and piping load will be about 480 Btu/hr. A high efficiency 1/3-HP blower and water pumps operating on a 50% duty cycle will add an additional 720 Btu/hr; thus, the average load due to system losses will be about 0.1 ton.

The total peak cooling load will therefore be 14.63 tons plus 0.7 tons, or 15.33 tons. Since the chiller provides a 15°F difference between supply and return water temperatures, the cooling capacity will be at a ratio of 95.86 gallons of stored chilled water per ton-hour of required storage. Therefore, the nominal storage capacity for the defined peak period will be 1470 gallons. If ethelyne-glycol is added to the storage water for winter freeze protection, the volume will increase by about 15% because of the lower specific heat of the water-glycol mixture.

Assume that a 1500-gallon cylindrical insulated tank has been selected as the storage unit for a typical CWS system. The external dimensions of the tank would be approximately 6½ feet in diameter and about 11½ feet in length, with an internal volume of about 201 cubic feet. Total weight of the filled tank, insulation, and hardware would be about 14,000 pounds.

C. System Dynamics and Operating Costs

The dynamics of operation and optimization of chiller selection were carried out using the graphical analysis shown in figure 7. First, the direct load data from table 1 were plotted for the 24-hour period of the maximal cooling load day of the year. After adding system losses to the basic load it became apparent that the 2.77-ton peak load fit well within the assumed peak period, and that the real-time cooling loads at the beginning and end of the peak period were well balanced at about 1.6 tons. This balance indicates that the "peak shaving" effect would reduce power demand near the peak period as well as eliminate all condenser power during the 7 peak hours.

After plotting daily temperature variations, a trial-and-error procedure was used to minimize condenser capacity by operating the condenser as long as practical during the cool night and morning hours. Capacity was incrementally reduced until the off-peak run time was sufficient to fill the storage unit to capacity 1½ hours before the peak period. Note that during the off-peak operation period from midnight to 11:30 AM, the excess cooling capacity accumulates gradually as 42°F water in the supply side of the storage tank. The area between the "off-peak operation" curve and the "direct-load + losses" curve between midnight and 11:30 AM is identically the 15.33 ton-hours of cooling required during the 7 peak hours. Therefore, the chiller operation sequence is as follows:

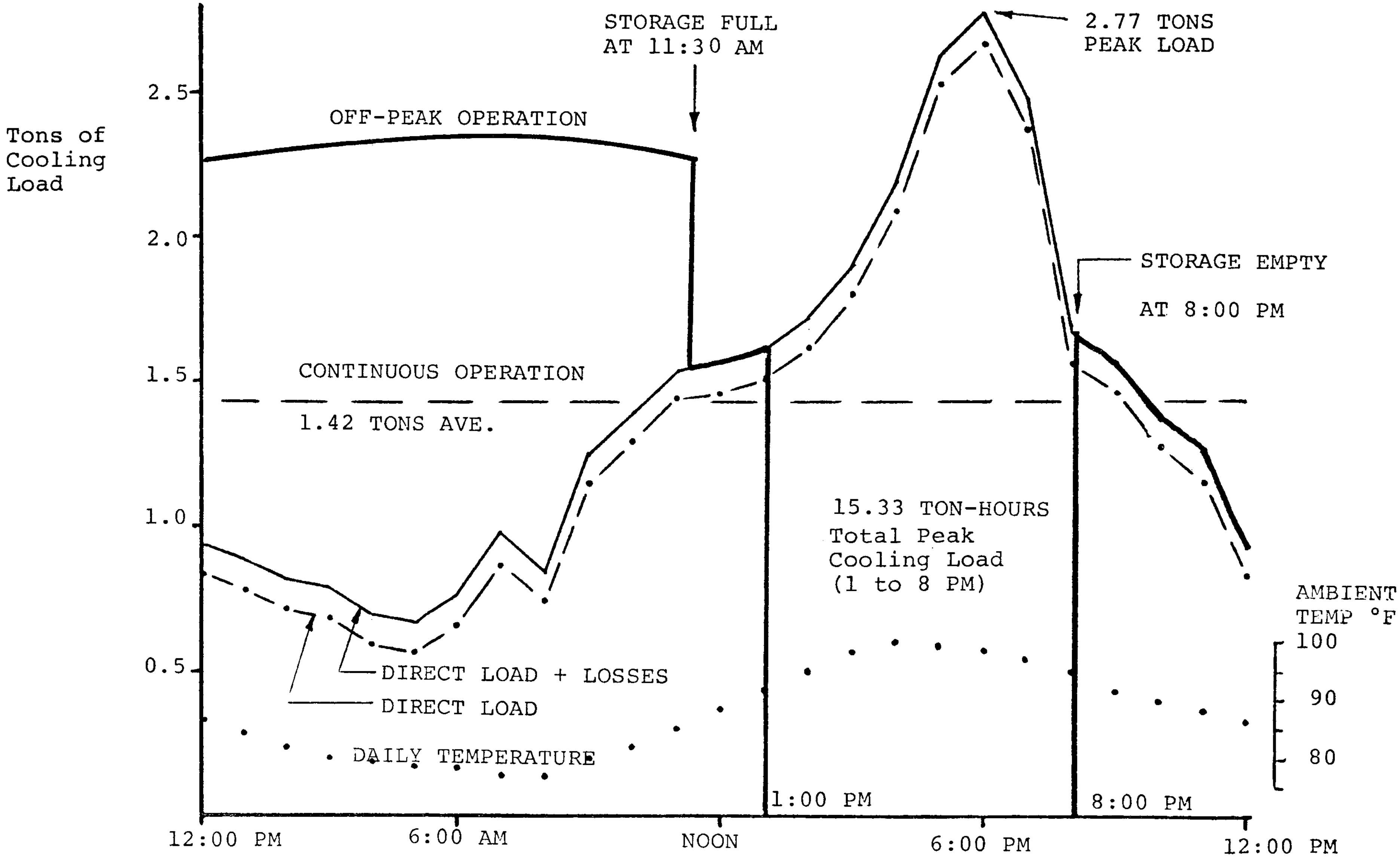


Figure 7

SYSTEM DYNAMICS - CHILLED WATER SYSTEM

midnight to 11:30 AM - Full capacity chiller load
11:30 AM - Storage full
11:30 AM to 1:00 PM - Chiller operates at 1.5-ton level to cool real-time load
1:00 PM to 8:00 PM - Chiller off, blower and coil pump remain on
8:00 PM to 12:00 PM - Chiller operates between 1.6-ton and 0.9-ton level to cool real-time load

It is important to note that the data of figure 6 imply that the EER has a value of 8.82 Btu/hr-watt at the average off-peak temperature of 82°F compared to an EER of 6.97 Btu/hr-watt at the peak average temperature of 98°F. Therefore, the off-peak mode of operation provides a gain in refrigeration efficiency of about 26% as a result of condenser operation with the cooler night air. Moreover, the only electrical energy consumed during the 7 peak hours is the power required to pump chilled water from storage and power to operate the blower.

y 1.5% EER impr./°C.

The numerical data which describe the system dynamics of the CWS system are summarized in table 3. The system load (column 4) has been translated into kilowatt-hours of energy (column 6) using the data from figure 6. The energy consumption data have then been converted into hourly cost of operation (column 8) using the time-of-day rate structure developed in section I. C. of this report.

Table 3

ANALYSIS OF CHILLED WATER SYSTEM

MODE: OFF-PEAK
RATE: TIME OF DAY

Hour Ending	Ambient Dry Bulb Temp. (°F)	Applied Load (Ton -hr)	System Load (Ton -hr)	Stored Cooling Cumulat. (Ton-hr)	Total Kilo-watt-hours	Rate ¢/kwh	Total Cost ¢
1	84	.88	2.29	1.41	3.20	3.46	11.07
2	82	.81	2.31	2.91	3.12	3.46	10.80
3	80	.78	2.32	4.45	3.07	3.46	10.62
4	79	.69	2.33	6.09	3.04	3.46	10.52
5	78	.66	2.33	7.76	3.00	3.46	10.38
6	78	.76	2.33	9.33	3.00	3.46	10.38
7	77	.97	2.34	10.70	2.97	3.46	10.28
8	77	.84	2.34	12.20	2.97	3.46	10.28
9	80	1.24	2.32	13.28	3.07	3.46	10.62
10	82	1.39	2.31	14.20	3.12	3.46	10.80
11	85	1.53	2.28	14.95	3.23	3.46	11.18
12	88	1.56	1.94	15.33	2.87	3.46	9.93
13	92	1.61	1.61	15.33	2.51	3.46	8.68
14	95	1.72	0	13.61	0.33	10.38	3.43
15	98	1.90	0	11.77	0.36	10.38	3.74
16	100	2.19	0	9.52	0.42	10.38	4.36
17	99	2.62	0	6.90	0.50	10.38	5.19
18	98	2.77	0	4.13	0.53	10.38	5.50
19	97	2.47	0	1.66	0.47	10.38	4.88
20	95	1.66	0	0	0.32	10.38	3.32
21	92	1.57	1.57	0	2.45	3.46	8.48
22	90	1.38	1.38	0	2.09	3.46	7.23
23	88	1.25	1.25	0	1.84	3.46	6.37
24	87	.93	.93	0	1.35	3.46	4.67
TOTALS					49.83 kwh		192.71¢

Total Cost at RS Rate of 5¢/kwh = 249.15¢

The full day cost of operation for the design cooling load day, using the time-of-day rate, is $1.9271. This amount compares favorably to a daily cost of $2.4915 using the 5¢/kwh residential rate.

V. ICE STORAGE SYSTEM ANALYSIS

A. System Description

There are several possible configurations for an ice storage system. The configuration chosen is simple and is also comparable to the chilled water system studied with the exception that condensing unit size is slightly larger and storage volume is much smaller.

A Dunham Bush AIPC-3 chiller was selected on the basis of ice storage and space cooling requirements. The water chiller evaporator is in parallel with the ice-building evaporator; two solenoid valves allow only the water chiller evaporator to be used for direct space cooling. The ice-building coils are built into a 300-gallon insulated fiberglass tank. An expansion valve is located just outside the tank. At present, no tank/coil combination of this type is commercially available in a 300-gallon size, but A. O. Smith Co. has produced a similar tank/coil arrangement with a 108-gallon capacity, and several companies produce very large commercial ice banks.

Figure 8 describes the basic ISS configuration used for this study. Note that there are three water loops involved. The first pumps water from the chiller to the coil. The second pumps water from storage to the coil. The third is a chilled-water bypass loop that uses a thermostatically controlled valve so that only the necessary amount of chilled water passes through the coil to cool the space. The remaining

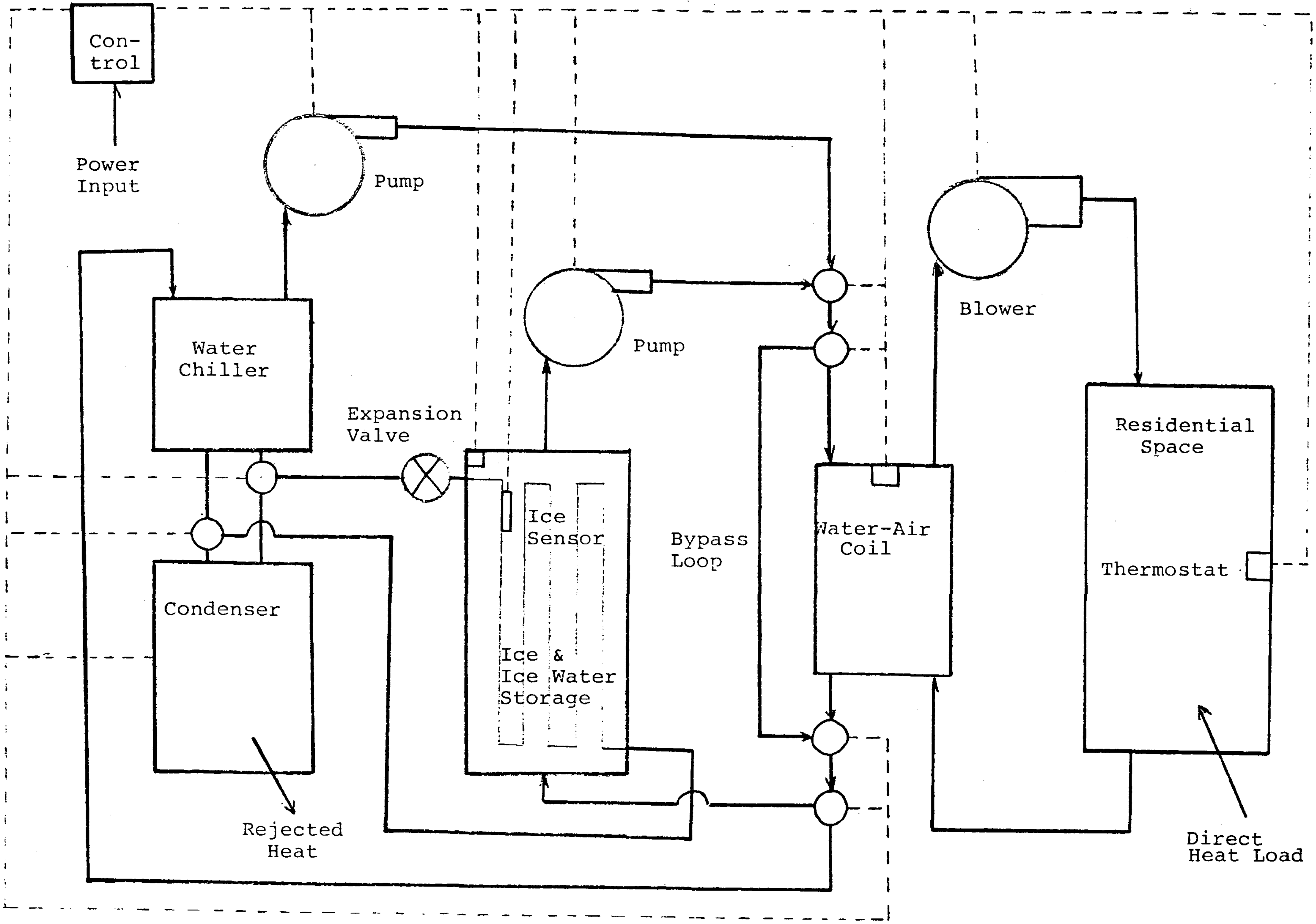


Figure 8

ICE STORAGE SYSTEM DIAGRAM

chilled water is diverted back to the storage tank. The 5-gpm chiller loop pump operates continuously during the peak period to assure uniform ice melting. The space is cooled by a 3-ton capacity water coil and 1200-cfm blower that is thermostatically controlled.

The principal advantage of a phase change TES unit is that the storage volume needed is greatly reduced as a result of the latent heat of fusion for ice. In addition, the ISS provides a uniform water temperature to the coil for most of the peak period which improves coil performance and simplifies design. A low water temperature, 33°F compared to normal 42°F, could be provided to improve dehumidification, which is important for comfort in the Central Texas area.

One of the disadvantages of the ISS is that a slightly larger condensing unit capacity is required for ice building. The coefficient of performance (COP) of a condensing unit being used to build ice is less than that of a similar unit used to chill water. The reason is the lower suction pressure on the compressor when building ice on the evaporator coil. The AIPC-3 unit capacity was derated by 25% for ice building for this reason. This percentage is an estimate; only actual system testing will provide accurate data on the capacity reduction for ice building. Figure 9 shows the unit's load characteristics versus ambient temperature. An additional curve which includes the power consumption of the pumps and blower is plotted along with the standard unit curve.

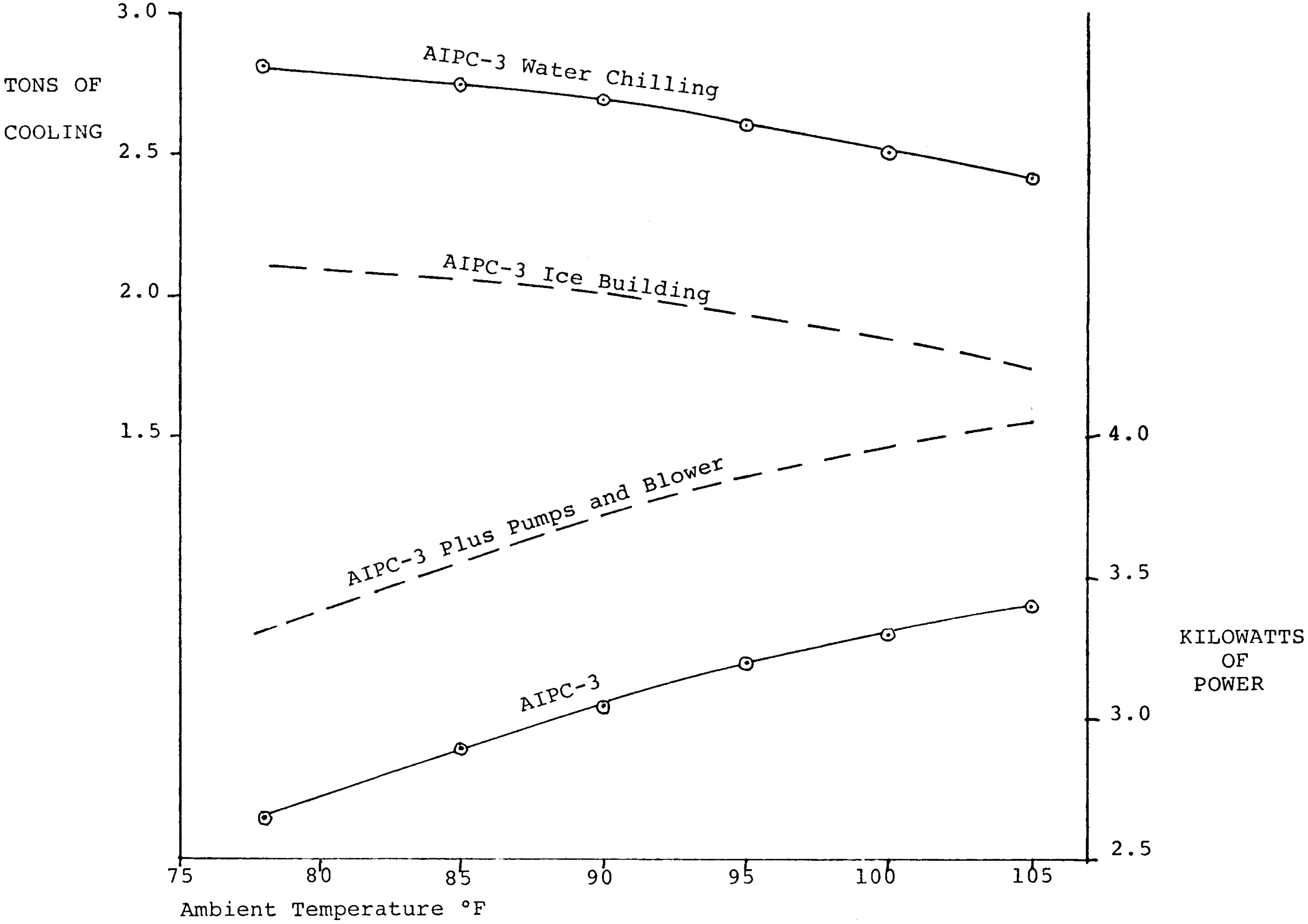


Figure 9

LOAD CHARACTERISTICS - ICE STORAGE SYSTEM

B. System Losses and Storage Requirements

As with the CWS, the cooling requirement for the space is 14.63 ton-hours during the 7-hour peak period. Therefore, additional capacity is required to make up system losses. The major losses are due to the heat gain through the 300-gallon storage tank's walls and piping insulation, and the heat generated in the moving fluid due to pump and blower work. Using 8-inch thick, low-density polyurethane insulation, the tank and piping load would be about 330 Btu/hr. This is 31% less than the comparable load for the CWS. Storing ice water results in larger heat flux through the tank wall than storing 42°F chilled water; however, the benefits of smaller surface area for the 300-gallon tank, as opposed to the area of a 1,500-gallon tank, far outweigh this drawback. After including 720 Btu/hr due to the water pumps and the blower, the average load due to ISS losses is about 0.09 ton.

As a result, the total applied load during the peak period is 15.26 ton-hours. It was determined that 1,015 pounds of ice will provide all of the peak cooling requirements. The ice tank contains a matrix of 288 feet of 3/8-inch copper tubing in parallel rows. A 1½-inch ice thickness accumulates on the tubing, and an ice limit sensor stops the freezing process when full thickness has been reached. Beyond this thickness further ice building would be less efficient because of the insulating effect of the ice build-up on the coil. When the storage tank is at full capacity, the tank contains approximately 57% ice water and 42% ice. The cylindrical tank with insulation would be about 5 feet in diameter and 5.3 feet high. Total weight of the filled tank, insulation, and hardware would be about 3,000 pounds.

C. System Dynamics and Operating Costs

A graphical analysis was used to evaluate the optional dynamics of the ice storage system. Figure 10 shows thermal load data plotted as a function of the time of day. The peak period total load of 15.26 ton-hours and peak load of 2.76 tons are representative of the maximum cooling loads that a typical residence with ISS would experience.

Ice building was started at midnight in order to maximize condensing unit performance by operating with cool nighttime temperatures. The amount of capacity available for ice building was calculated on an hourly basis by subtracting the "Direct Load + Losses" from the chilling unit's maximum capacity, and then taking 75% of this amount to compensate for the reduced efficiency when building ice. The resultant hourly capacity values were summed until the required storage of 15.26 ton-hours was reached. This full storage condition occurred at 10:10 AM. The "Off-Peak Operation" curve in figure 10 is a result of this graphical analysis procedure. The ice storage system's operational sequence is as follows:

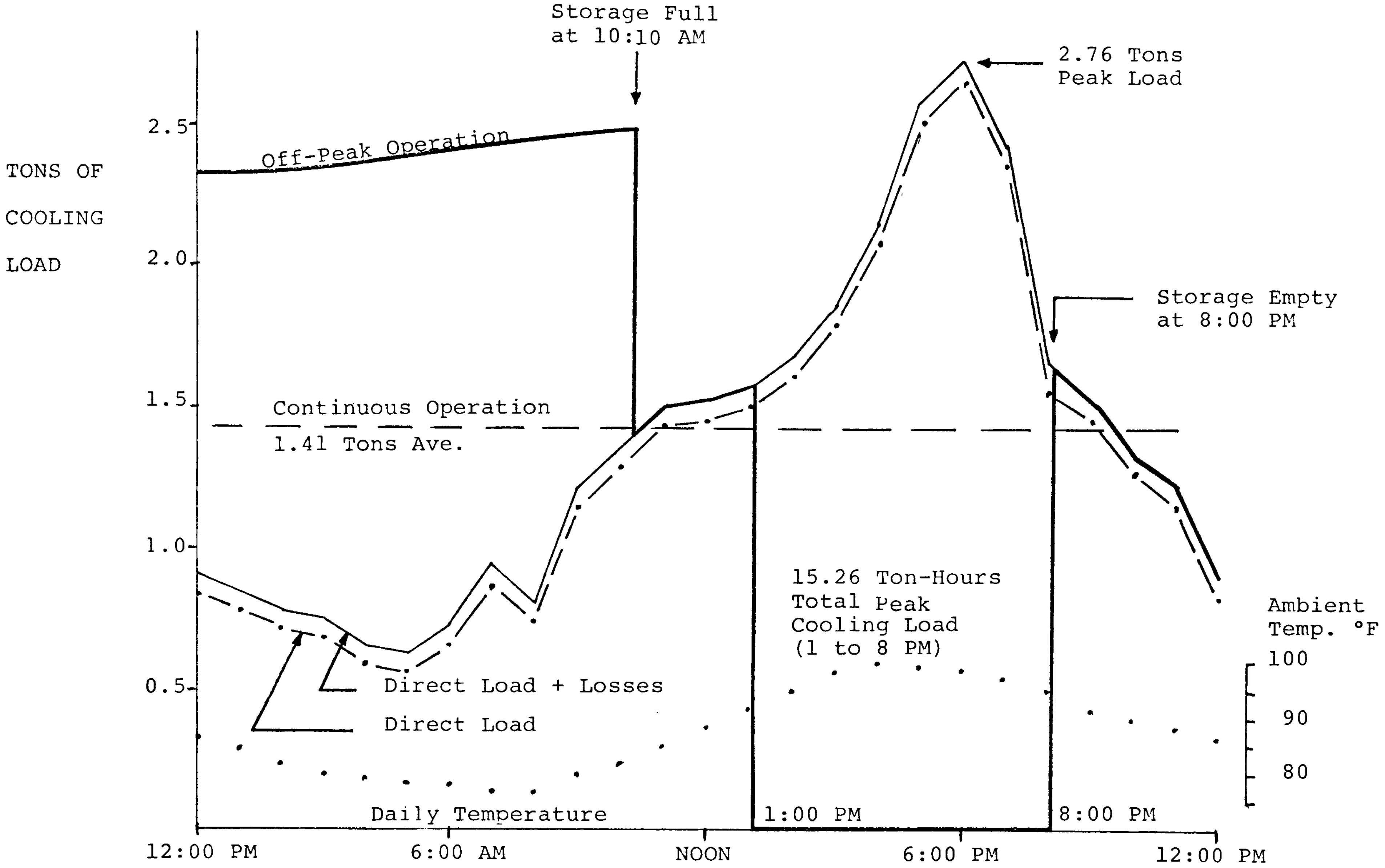


Figure 10

SYSTEM DYNAMICS - ICE STORAGE SYSTEM

Midnight to 10:10 AM - Full capacity chilling and ice building
10:10 AM - Storage full
10:10 AM to 1:00 PM - Only chiller operates to cool real-time load
1:00 PM to 8:00 PM - Unit off, ice water from storage to cool peak period load
8:00 PM to midnight - Only chiller operates to cool real-time load

If we compare an average ice-building and water-chilling EER of 8.42 Btu/hr-watt for the off-peak period with an EER of 6.98 Btu/hr-watt for the peak period, we see that there is a gain in refrigeration efficiency of about 21% as a result of operation during the cooler night temperatures. Thus, the off-peak operation mode provides a significant energy savings.

Table 4 summarizes the ISS dynamics and tabulates kilowatt-hour consumption and cost. It was found that for a time-of-day rate structure, the daily cost of operation for this maximum cooling load day is $2.0131. A flat rate of 5¢/kwh results in a daily operating cost of $2.5385. These costs are very similar to those for the chilled water system and compare favorably with costs for the typical central system.

Table 4

ANALYSIS OF ICE STORAGE SYSTEM

MODE: OFF-PEAK
RATE: TIME OF DAY

Hour Ending	Ambient Dry Bulb Temp. (°F)	Applied Load (Ton -hr)	System Load (Ton -hr)	Stored Cooling Cumulat. (Ton-hr)	Total Kilo-watt-hours	Rate ¢/kwh	Total Cost ¢
1	84	.87	2.32	1.45	3.52	3.46	12.18
2	82	.80	2.34	2.99	3.45	3.46	11.94
3	80	.77	2.35	4.57	3.38	3.46	11.69
4	79	.68	2.36	6.25	3.34	3.46	11.56
5	78	.65	2.37	7.97	3.31	3.46	11.45
6	78	.75	2.41	9.63	3.31	3.46	11.45
7	77	.96	2.47	11.14	3.27	3.46	11.31
8	77	.83	2.43	12.74	3.27	3.46	11.31
9	80	1.23	2.51	14.02	3.38	3.46	11.69
10	82	1.38	2.51	15.15	3.45	3.46	11.94
11	85	1.52	1.63	15.26	2.14	3.46	7.40
12	88	1.55	1.55	15.26	2.07	3.46	7.16
13	92	1.60	1.60	15.26	2.24	3.46	7.75
14	95	1.71	0	13.55	0.53	10.38	5.50
15	98	1.89	0	11.66	0.53	10.38	5.50
16	100	2.18	0	9.48	0.53	10.38	5.50
17	99	2.61	0	6.87	0.53	10.38	5.50
18	98	2.76	0	4.11	0.53	10.38	5.50
19	97	2.46	0	1.65	0.53	10.38	5.50
20	95	1.65	0	0	0.53	10.38	5.50
21	92	1.56	1.56	0	2.18	3.46	7.54
22	90	1.37	1.37	0	1.87	3.46	6.47
23	88	1.24	1.24	0	1.66	3.46	5.74
24	87	.92	.92	0	1.22	3.46	4.22
	TOTALS				50.77 kwh		201.31¢

Total Cost at RS Rate of 5¢/kwh = 253.85¢

VI. ECONOMICS OF OFF-PEAK COOLING

The preceding sections of this report have examined the technical feasibility and operating dynamics of two off-peak cooling systems, the CWS and the ISS. It should be apparent that no major technical innovations are required to design and install either of these AC/TES systems. Both systems use conventional condensing units, air coils, valves, pumps, and other standard HVAC hardware. The only item that would require some development and testing is the moving insulated tank divider in the CWS system which separates the supply water from the return water.

In spite of the technical simplicity of both AC/TES systems, it will be the economic factors that dictate how attractive these concepts are and how rapidly they might be adopted. This economic evaluation, as with most energy system evaluations, will consider both the potential savings due to reduced operating costs and the incremental capital costs required to install an AC/TES system.

A. Annual Operating Costs

Let us now consider a summary of the daily cost of operation for each of the three systems analyzed in sections III, IV, and V. All of these costs were calculated for the maximum heat load day of the year, using both a residential rate (RS) and a proposed time-of-day rate (TD).

These costs are as follows:

System	Rate Structure	Max. Load Day Cost
TCS	RS	$3.20
TCS	TD	$4.29
CWS	RD	$2.49
CWS	TD	$1.93
ISS	RS	$2.54
ISS	TD	$2.01

These daily costs can be extrapolated to determine the annual cost of operation by one of two methods. First, we can calculate the ratio of the total seasonal cooling load to the load on the maximum load day. This ratio indicates that the full-season operation of an air conditioner in Austin is equivalent to about 120 days of operation under maximum load day conditions.

Another method which allows extrapolation to annual operating costs is to compare the daily cost of operation of the TCS to the annual cost implied by reference 11 (see figure 2), using the average residential rate of 5¢/kwh. This method leads to a value of 130 days of maximum load day operation for the equivalent of a full season's operation. These two methods give approximately the same results; however, the 130-day equivalent was used to determine the following annual operating costs:

System	Rate Structure	Annual Operating Cost
TCS	RS	$416.06
TCS	TD	$557.34
CWS	RS	$323.90
CWS	TD	$250.52
ISS	RS	$330.00
ISS	TD	$261.70

Since the typical central system (TCS) is the basis for comparing the two AC/TES systems, the annual savings in operating costs can be determined. Therefore, the savings in annual operating costs for the thermal storage systems, relative to the TCS, are as follows:

System	Rate Structure	Annual Savings
CWS	RS	$ 92.16
CWS	TD	$306.82
ISS	RS	$ 86.06
ISS	TD	$295.64

The savings indicated above for operation at current residential rates are a result of the 21 to 22% greater average efficiency for the AC/TES units. This efficiency advantage is due primarily to the fact that storage system condensing units are cooled mostly with nighttime air, instead of the hotter daytime air used to cool the TCS condensing unit. This mode of operation saves money and energy, and represents an important energy conservation feature of these AC/TES systems, as indicated below:

System	Annual kwh	% Energy Saved Compared to TCS
TCS	8321	-
CWS	6478	22%
ISS	6600	21%

The larger savings identified for these same systems with TD rates result primarily from the fact that the CWS and ISS consume only about 6% of their daily energy requirement during the 7 peak-demand hours of the day when the rates are highest. However, the operating cost savings for TD rates depend almost totally upon the premium charged for power during the peak hours, and that premium is assumed to be 200% for these analyses.

B. Analysis of Capital Costs and Break-even Periods

Estimation of capital costs for the CWS and ISS concepts involves many uncertain factors. However, the main uncertainty relates to how low the cost of AC/TES system components would go, particularly the cost of the condensing unit, if mass production techniques were applied. This is with reference to today's low cost of TCS components that are achieved through mass production techniques. Because of this uncertainty with respect to the degree that CWS and ISS systems might be commercialized, the capital cost estimates are presented on two levels. One level assumes only moderate-volume production of AC/TES systems, and the other assumes high-volume production of these units. The TSC capital and labor costs are the baseline for comparison and were obtained by averaging system quotations from several commercial sources. These system costs, which include capital and labor for installation, are as follows:

Total System Costs - Initial Capital and Labor

System	Production Volume Moderate	 High
TCS	not appl.	$1800
CWS	$4400	$2800
ISS	$4100	$2700

These estimates are based on the judgement that the cost of CWS and ISS condenser units in mass-produced quantities would approach the cost of TCS condensing units. This means that labor and capital cost differences between the two AC/TES units and the TES would be almost totally a function of the storage tank cost and the labor costs required to install the tank. Therefore, the incremental cost of an AC/TES system above the cost of a typical central system is estimated to be between $900.00 and $1000.00 if all systems are mass-produced.

From these calculations of annual operating costs and incremental system costs we can determine the "break-even period" for the AC/TES systems. The break-even period is defined as the ratio of incremental system cost to annual savings, and represents an approximate measure of the time period required to recover a given investment. The following break-even periods were calculated with the assumption that time-of-day rates were used to determine savings.

Break-even Periods

System	Production Volume Moderate	 High
CWS	8.5 years	3.3 years
ISS	7.7 years	3.0 years

VII. CONCLUSIONS

A variety of conclusions can be drawn from this study when the operational, technical, and economic factors are considered together in a retrospective assessment of AC/TES systems:

1. Since the cost to operate air conditioning is the largest component of a typical Texas residential energy bill, it should be the prime target for energy conservation efforts in the home.
2. Realistic rate structures for electrical energy, such as time-of-day rates, can act as strong incentives for customers to reschedule tasks to off-peak hours and can also encourage manufacturers to develop and market AC/TES systems.
3. Both the CWS and ISS show a remarkable ability to reduce peak power demand and total energy required to levels far below those required by a typical central air conditioning unit. In fact, the CWS system requires 40% less peak power and consumes 22% less electrical energy than a TCS operating under identical heat load conditions.
4. Current residential rates do not offer enough of an incentive, in terms of reduced operating costs, for residential customers to switch to an AC/TES system.
5. If time-of-day rates were adopted and included a

200% permium for power delivered during peak hours, an AC/TES system could provide savings of about $300 per year. These savings in operating costs would be sufficient to recover the higher first cost of the AC/TES system in about 3 or 4 years.

6. A full-scale demonstration project, comparing identical houses--one with a TCS and one with an AC/TES--would provide utilities with valuable performance data and enhance the prospects for commercialization of off-peak cooling systems.

It should be clear from the system diagrams of the CWS and ISS concepts, figures 5 and 8, that the success of these systems does not depend upon any technological breakthroughs. Rather, as previously mentioned, it is the economic factors that will dictate whether or not the AC/TES will become a viable concept for residential air conditioning. Most important of the economic forces is the manner in which utilities charge for power during the peak hours of the day.

One of the many challenges facing utilities and regulatory agencies today is to see that electrical rates more accurately reflect the true cost of service to each class of customer, particularly during peak consumption hours of each day. If future rate structures can approach this ideal, and the complementary metering and billing methods can be implemented, then the proper economic incentives will exist for the full commercialization of AC/TES systems.

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