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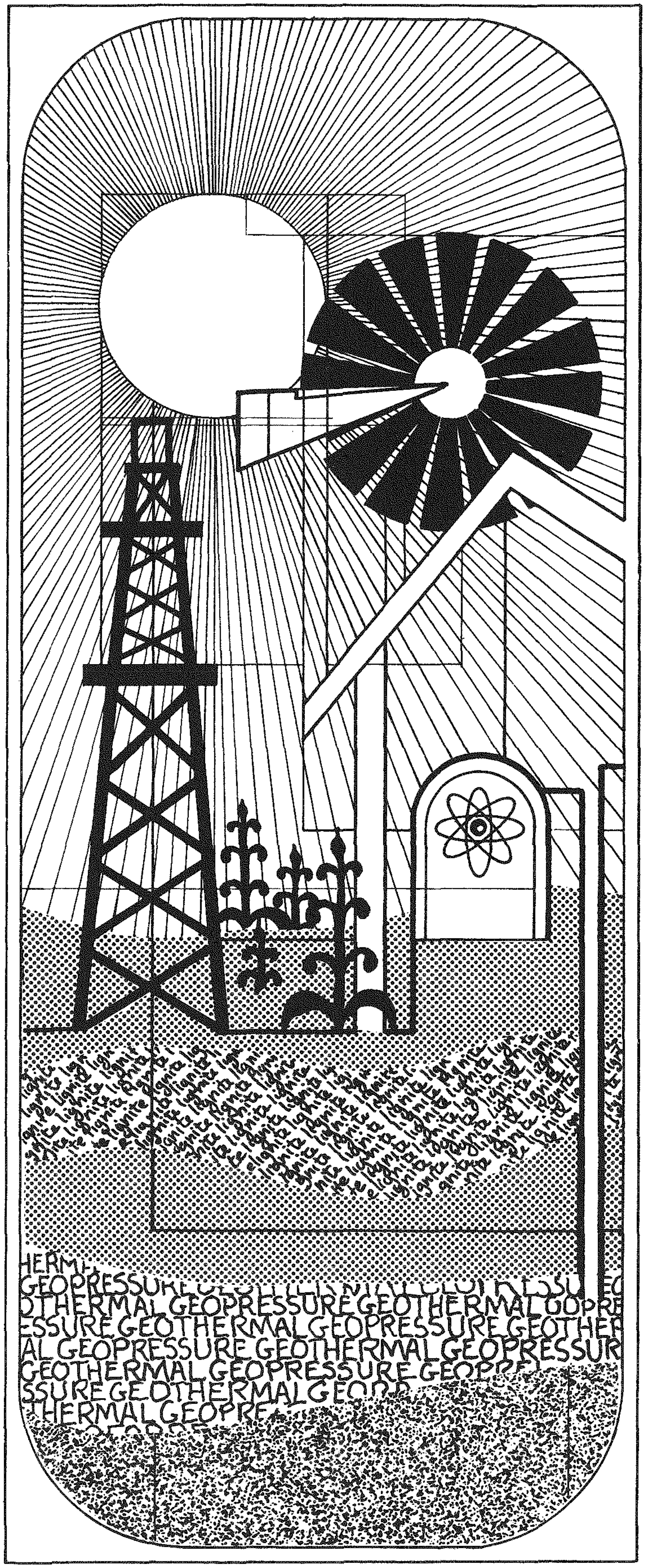

Texas Energy Development Fund

DEVELOPMENT OF THE COMMERCIAL
AIR CONDITIONING WITH THERMAL ENERGY
STORAGE CONCEPT
PHASE I

TENRAC/
EDF-041

MASTER

TEXAS ENERGY
& NATURAL RESOURCES
ADVISORY COUNCIL

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DISCLAIMER

The principal investigator wishes to acknowledge the support and encouragement given to this project by Dallas Light and Power Company; however, the conclusions and recommendations contained in this report do not necessarily represent the views of Dallas Light and Power Company.

In the interest of timeliness final editing has not been done by the TENRAC staff, but the report is published as submitted by the project investigators.

DEVELOPMENT OF THE COMMERCIAL AIR CONDITIONING WITH THERMAL-ENERGY-STORAGE CONCEPT:

PHASE I

by

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FINAL REPORT

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EXECUTIVE SUMMARY

The objectives of this development project have been to explore the technical and economic feasibility of Air Conditioning with Thermal Energy Storage (AC-TES) for commercial applications. AC-TES systems save energy and KW demand by producing cooling during utility off-peak hours, then drawing cooling from storage during hours of peak utility load. Preliminary analyses have shown that systems based upon ice and chilled water storage have greater near term potential than systems based upon chemical storage or freon accumulation.

The project investigators developed probable time-of-day rates, system concepts, and cost data for two AC-TES systems. These storage cooling units were sized to replace a conventional 35-ton DX rooftop condenser. Performance and economic analyses of these systems suggest that payback periods of 5 to 7 years can be obtained with this cooling concept, if electric utilities offer progressive time-of-day rates. Widespread adoption of the AC-TES concept by commercial and industrial users should result in about a 15% reduction in summer peak demand for a typical electric utility in Texas.

It is recommended that the PUC, TENRAC, and electric utility companies should play a major role in demonstrating the merits of thermal storage cooling to electric power customers. Implementation of progressive time-of-day rates and effective education of utility customers will be necessary for the successful commercialization of the AC-TES concept.

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* WSD = Worst Summer Day
TSD = Typical Summer Day

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1. INTRODUCTION

During the past 25 years, Texans have come to appreciate and to depend upon the comfort level provided by refrigerated air conditioning. In fact, our dependency upon refrigerated air in office buildings and factories has reached the point where most employees are very sensitive to small changes in temperature and humidity. A recent GOER report [1]* indicates that between 30% and 50% of the energy consumed by a typical office building in Texas is for air conditioning. Similar percentages apply to air conditioning energy for small and medium-sized manufacturers.

Recent nationwide efforts of saving cooling energy by raising thermostat settings appear to be of dubious value because the savings in energy cost is often offset by decreased productivity of employees and increased absenteeism. If the productivity of the Texas work force is to be maintained at a high level, we must look for more efficient means of air conditioning office buildings and factories.

Increased air conditioning efficiency and reduction of on-peak electric demand appear to be the most practical approaches to controlling the utility costs for commercial and manufacturing buildings.

This report describes the evaluation of a cooling system which has the potential to save 10% of the energy and 50% or

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* Numbers in brackets indicate a technical reference which is listed in the Appendix at the end of this report.

more of the operating cost for cooling commercial buildings, with no degradation of comfort level in the buildings. This system concept is Air Conditioning with Thermal Energy Storage, hereafter referred to as the AC-TES concept.

A. THE DEMAND PEAKING PROBLEM IN TEXAS

The relatively high level of economic prosperity which Texans have enjoyed for the past decade is not only creating wealth for Texans--but also a wealth of problems. As new companies and employees have moved from all over the United States to the "heart of the sun belt", local governments have been struggling to keep up with the growth in demand for municipal services. New roads, new water service, new sewage service, as well as additional police and fire protection are needed for developing suburban areas. The rapid expansion of population in the major metropolitan areas (Houston, Dallas-Ft. Worth, San Antonio) has caused severe traffic problems, deteriorating environmental conditions, and has pushed several major gas and electric utilities into situations that are approaching their system capacity limits.

Of all the stress factors confronting our energy utilities in Texas today, the one that appears to be most critical is peak demand for electric energy. This peak demand for electric power occurs during the summertime because the demand for air conditioning is at its peak during the months of June, July, August and September. For these summer months it can be shown that there is a direct correlation between ambient temperature, total air conditioning load, and total demand for electric power. Consider the data shown in Figure 1. This illustrates the time variation of total system power output for the Dallas Power & Light Company on August 22, 1980, one of the hottest days of the year, and February 4, 1980, a typical winter day. The significance of Figure 1 is that a new system peak demand record of 2844 Megawatts was set on August 22. In fact, new system demand records have been set in three of the past four summers as indicated below.

TABLE 1. DP&L PEAK DEMAND, 1974-1980

Year	DP&L System Peak Demand	Total Season Cooling Degree-Days (70°F Base)
1974	2408 Megawatts	1447
1975	2354 Megawatts	1601
1976	2378 Megawatts	1339
1977	2495 Megawatts	2200
1978	2609 Megawatts	2081
1979	2473 Megawatts	1559
1980	2844 Megawatts	2233

Referring to Figure 1, note the relationship between peak demand and ambient temperature on the record demand summer day. The minimum demand of 1570 Megawatts occurs within 2 hours of the minimum temperature of the day, 76°F. The maximum demand of 2844 Megawatts occurs within 1 hour of the maximum temperature for the day, 105°F.

The typical winter day load profile is included in Figure 1 to illustrate the imbalance between summer and winter demand.

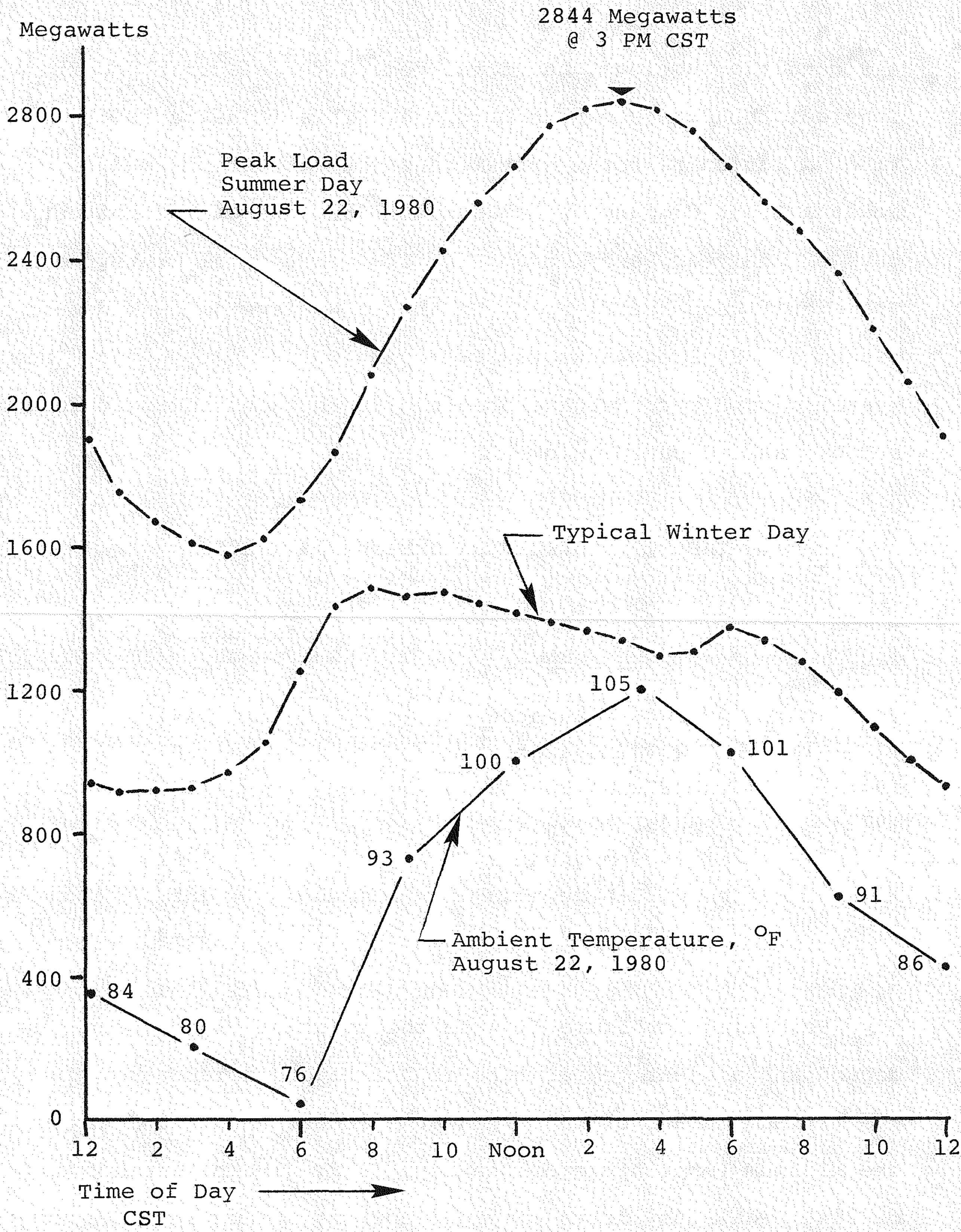

FIGURE 1. Dallas Power & Light Company
1980 System Demand Data

The demand curve for February 4, 1980 is representative of a typical winter day for the DP&L system. Therefore, the capacity difference between August 22 and February 4 of the same year is a rough indication of the generation capacity associated with air conditioning. In this case it appears that about 50% of the 1980 peak system load is due to the combined effects of residential, commercial, and industrial air conditioning. This percentage is representative of many other major utilities in Texas.

The economic significance of these curves is that all electric utilities must build sufficient generation capacity to meet the peak load requirements of each year, plus a reserve capacity of about 15%. In the fall, winter, and spring seasons, much of this expensive generating capacity is idle. Therefore, the imbalance between demand in the summertime and demand at other times of the year results in relatively poor utilization of the total system capital investment.

This effect is particularly important because of today's relatively high construction costs for electric utilities. In recent years the cost of new generation capacity has risen dramatically to values approaching $1,300 per installed Kilowatt. So, if a major utility company has 1,000 Megawatts of idle capacity in the wintertime, this is equivalent a multi-million dollar investment sitting idle, earning no income. This "idle generation" effect is certainly one of two major factors that is contributing to today's higher rates for all utility customers. The other factor is, of course, rapid escalation of all fuel costs.

The solution to the demand peaking problem in Texas is fairly obvious to all concerned parties--Energy Conservation and Load Management. However, the utilities and the electric power customers agree that it will take time and considerable capital to implement these solutions. The peak summer demand for electric power can be reduced to some degree by the gradual installation of more efficient cooling systems and the adoption of a wide range of other energy conservation measures.

Load management holds even greater potential than conservation for improving the capital utilization factor for electric utilities. The basic strategy of load management is to shift the daytime use of power to "off-peak" periods, and thereby flatten the system load curve during normally high consumption periods. Many utilities offer lower "off-peak" electric rates and/or time-of-day rates as an incentive to shift demand to times other than the noon to 8 PM peak period. Some industries have rescheduled production activities from 1st shift to 2nd or 3rd shift to take advantage of the lower "off-peak" rates. However, because of established work habits and the necessity of paying shift premiums to workers on 2nd and 3rd shifts, the overall consumer response to "off-peak" electric rates in Texas has been minimal.

B. BACKGROUND INFORMATION ON AC-TES

One of the most promising concepts for "shaving the peak" off of the summer demand curve is Air Conditioning with Thermal Energy Storage, or AC-TES. This type of cooling system operates on a very simple principle: Maximize the system duty-cycle at a time when the condenser efficiency is at a maximum. Condenser efficiency (BTUs of cooling per watt-hour) usually improves significantly at night because the nighttime air temperature is typically 15^{O}F to 20^{O}F cooler than during the day. From a practical standpoint this efficiency gain can be accomplished by operating the cooling system at night and storing the cooling capacity in the form of chilled water, ice, or use of chemical storage techniques. This type of system acts as a "thermal flywheel" by storing cooling capacity at night and retrieving it during the following day for comfort cooling. A typical system diagram to accomplish the storage and retrieval functions is shown in Figure 2.

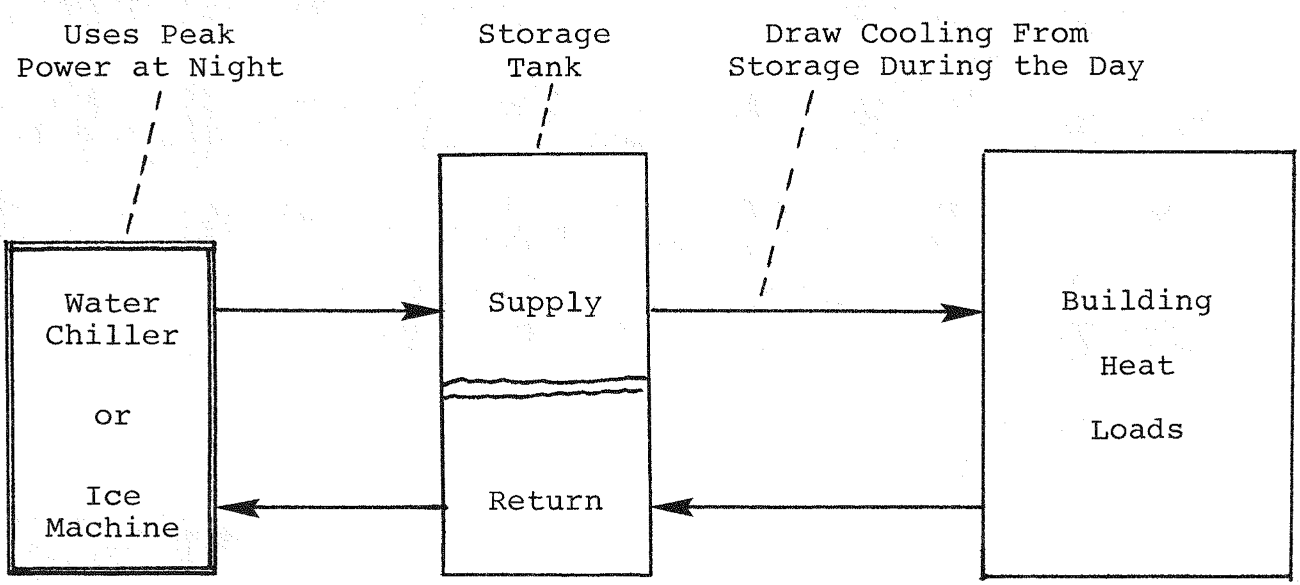

FIGURE 2. AC-TES System Diagram

For the consumer, an AC-TES system has two fundamental advantages over conventional air conditioning units:

(1) A gain in overall energy efficiency (EER) results from condensing with cooler nighttime air (in the range of 8% to 14% higher for typical Texas weather conditions).

(2) The KW demand required to operate the cooling system during peak utility periods (usually noon to 8 PM) is reduced to about 10% to 20% of the peak KW demand for a conventional system, since only blowers and pumps operate during the "on-peak" period.

If "off-peak" rates are available to the consumer, then substantial reductions in the cost to provide comfort cooling can be achieved. Further information on the importance of "off-peak" rates and the importance of specific meter connections are given in Section 2B of this report.

For the utilities, the advantage of this concept is that it can begin to "shave the peak" of the summertime demand curve. This, in turn, can reduce the requirements for future capital investment and relieve some of the financial stress now felt by many utilities in Texas. It is estimated that if commercial and industrial AC-TES systems were in wide-spread use, the summertime peak demand for a utility could be reduced by 20% to 30% in most major Texas cities.

Other significant background data on thermal storage cooling comes from a review of recent research and demonstration projects in this field. During the past six years the U. S. Department of Energy and various state energy agencies have sponsored more than 25 R & D projects that analyzed the performance of air conditioning with thermal storage and heat pumps with thermal storage. Almost all of these projects have considered residential applications. Some projects have investigated annual-cycle storage systems such as the "ACES" project at Oak Ridge, Tennessee; however, most projects have examined the peak load reduction and energy saving benefits of daily-cycle storage systems.

In the State of Texas, three recent studies have verified the energy savings and "peak shaving" benefits of AC-TES, using computer simulated weather and performance parameters. These studies have resulted in the following reports;

(1) R. Bywaters and G. Jones, "Power Reduction in Residential Air Conditioning Systems Through the Use of Thermal Energy Storage", an R & D report prepared in conjunction with the University of Texas at Austin for the Governor's Energy Advisory Council, Texas, September 24, 1976.

(2) R. Bywaters and D. Hannan, "An Evaluation of Technical Options for Off-Peak Air Conditioning Systems", an R & D report prepared in conjunction with the University

of Texas at Austin, funded by Exxon USA, May 31, 1977.

(3) R. Bywaters, J. Holman, M. Larson, "An Investigation of the Conservation Potential of Residential Heat Pumps with Thermal Energy Storage", an R & D report prepared in conjunction with Southern Methodist University for the Texas Energy Advisory Council, Project C-4-2, May 15, 1979.

A careful examination of the results of these and other residential R & D programs shows that, in spite of the very positive peak load and conservation benefits, the economic viability of the concept fails for two basic reasons. First, the scale of the cooling unit (3 to 6 tons of cooling) is too small to generate cost-effective thermal storage. Second, it is not practical to implement time-of-day rates because TOD metering would be too expensive for the residential sector to implement.

Both of these items suggest that the entire emphasis of the thermal storage R & D programs should be shifted to larger buildings such as commercial buildings, manufacturing buildings, and other public buildings. The cooling capacity for these larger buildings is typically in the range of 25 tons to 300 tons. These larger facilities usually have KW demand metering as well as the usual KWH metering. The cost to modify these meters for TOD or "off-peak" billing would be justified by the size of the load.

The economics and technical feasibility of very large AC-TES systems (1000 tons and larger) have already been proven with the successful construction and operation of several large commercial buildings in the Southwestern United States.

Two additional economic factors work in favor of larger thermal storage air conditioners. First, the economics of scale work in favor of reducing the cost per ton-hour of storage capacity. Second, many commercial and industrial buildings already have water-chiller type of air conditioning equipment in place; hence there is no cost to convert from direct expansion cooling to water chiller operation, as there is in residential applications.

In summary, the results of recent thermal storage R & D programs suggest that the time has come to put major emphasis on a commercial-scale demonstration of the AC-TES concept.

C. AC-TES OPTIONS FOR THE EXPANDED COMMERCIAL SECTOR

In the context of this report the phrase "Expanded Commercial Sector" will be used to identify office buildings, shopping centers, hotels, motels, retail businesses, schools, health care facilities, and small-to-medium sized manufacturing companies. This revised definition of the "Commercial Sector" is useful for this study project because these types of buildings are prime targets for conversion to the AC-TES concept. Another way to define this target sector is to say that it includes all types of buildings <u>except</u> large industrial facilities and residential homes.

In the State of Texas, this Expanded Commercial Sector consumes approximately 18% of the total energy. About one-third of this 18% can be attributed to air conditioning. Therefore, the specific target for energy efficiency improvements with the AC-TES concept corresponds to about 6% of the total energy consumption in Texas.

At an early point in this development project it was decided to evaluate the general applications of various technical options for thermal storage. There are four options which deserve serious consideration. These are chilled water, ice, phase-change chemical, and freon accumulator. Earlier study programs have considered other energy storage methods (flywheels, batteries, compressed air) for implementing off-peak cooling; however, each of these other methods has severe economic limitations. See Reference [2] for further details.

This "first cut" evaluation assumed a standard heat load for a typical commercial structure, then applied this load to simple models of the four primary options. This standard heat load was defined as a twelve-hour transient load with a peak of 35 tons at 5 PM. The integral heat load for the day was assumed to be 250 ton-hours, or exactly 3×10^6 BTUs per day. These preliminary system evaluations assumed average summertime weather conditions for Dallas, Texas, of 91.3°F maximum temperature at 5 PM and a minimum temperature of 71.5°F at 6 AM.

For these conditions, it was noted that a typical rooftop DX (direct freon expansion) cooling system would generate a peak demand of 40.1 KW, and consume 43,513 KWH for a normal cooling season.

OPTION 1 - Chilled Water Storage

The basic chilled water version of a thermal storage system was illustrated in Figure 2. A water chiller is used to fill the supply side of a storage tank during the cooler nighttime hours. During the "on-peak" hours cold water at about $42^{O}F$ is drawn from storage to meet the real-time cooling load, and return water at about $57^{O}F$ is pumped back to storage. This concept uses mostly off-the-shelf HVAC components. Items such as the chiller, valves, pumps, and coils are standard designs. The specialty components needed to implement this concept are the timer/programmer and the storage tank(s).

The timer/programmer is the key to efficient operation of the chilled water system because optimum start/stop times must be derived for variable weather conditions and variable internal load situations.

The storage tank has one critical requirement for efficient operation: the supply and return water must be separated at all times in order to avoid irreversibilities that would occur with mixing of the two water streams. Various baffle and membrane schemes have been invented to avoid mixing in a common storage tank. The simplest solution to the mixing problem is to employ two separate tanks, or two concentric cylinder tanks; however, a cost penalty is incurred with this approach.

The preliminary evaluation of the chilled water system assumed the standard heat load and two different capacities for the water chiller. One condenser was sized at 465,000 BTU/hr capacity unit and the other had a capacity of 241,000 BTU/hr. The lower capacity system would run a much longer time at night to generate the same capacity of stored cooling. Seasonal energy consumption for the chilled water options are tabulated at the end of this section in Table 2.

OPTION 2 - Ice Storage

Ice storage cooling systems have been in use for many years and therefore can use standard components. However, off-peak ice storage has not been applied to any extent for the cooling of commercial buildings. Most ice storage cooling systems in the U. S. have been installed in churches to accommodate the heavy load on Sundays. Many church-based ice storage systems have been in use for over 35 years. Typically these small capacity systems will run day and night for four or five days during the week to store enough cooling capacity for the peak load on Sunday. Also, the dairy industries have used ice storage cooling for many years for the preservation and conditioning of milk products.

The primary advantage of ice storage systems is the smaller volume required to achieve a given storage capacity. Ice is a phase-change material with a heat of fusion of 144 BTUs per pound. A pound of water in a chilled water system (with a temperature split of 15°F) can only store about 15 BTUs of sensible cooling. Ice storage tanks usually require about an equal volume of ice and water; therefore, ice storage systems have about a five-to-one volume advantage over chilled water systems.

The principal disadvantage of ice storage, relative to chilled water storage, is that the basic cooling efficiency is significantly lower for ice. Since ice making requires a freon suction temperature of about 20°F (vs. about 37°F for chilled water), the electric energy required to produce a specified capacity (ton-hours) of ice storage will be about 10% to 15% greater than chilled water storage.

Ice systems also have problems associated with the proper flow of water in and out of the storage tank, and problems associated with the buildup of ice on coils and the resulting thermal resistance of this ice buildup. Commercial ice machines have solved most of these problems by use of air agitation, mechanical "harvesting" of ice and other innovations. However, these solutions usually require more energy which, in turn, leads to further degradation of the energy efficiency ratio for the ice machine. Nevertheless, ice storage cooling remains a viable option for commercial buildings because of its relatively low first cost and its five-to-one volumetric advantage over chilled water systems.

The model ice storage system used in the preliminary evaluation was based upon a standard Carrier condensing unit and a Chester-Jensen coil/storage tank. This combination was also evaluated in two capacity levels. The ice system capacities were selected to give off-peak run-times of about 7 hours and 12 hours for a typical summer day. The seasonal energy values for the ice storage systems are shown in Table 2 at the end of this section.

OPTION 3 - Phase-Change Chemical Storage

Eutectic Salts (including the Glauber Salts) can be used effectively for thermal energy storage by cycling these materials through a phase change. These salts can be frozen to store coolness and melted to release this coolness at a later time period. However, unlike ice these salts are an extremely corrosive compound. They are also hydroscopic and must be protected from moisture. Therefore, the most common method for using these salts for thermal storage is to package them in high density plastic trays or cylinders, then load these into a rack which spaces the components to allow for proper air flow. These storage units often resemble a large package of sausage. This packaging system allows for easy transportation and handling of the salts and prevents moisture contamination, but adds to the overall cost of the thermal storage system.

Cold air, at a temperature below the melting point of the salt, is blown through the rack of "sausages" during off-peak hours and this causes the salts to freeze. Later, during on-peak hours the salts give up their coolness to the airstream as they melt.

Eutectic salts used for thermal storage have some problems. The natural melting point of these salts is around 90°F, which is obviously too high to use for comfort cooling. The salts also tend to separate into liquid and solid layers and they sometimes display a change of thermal properties when cycled through many cycles of freezing and thawing.

Researchers have improved the thermal performance of these salts by adding borax as a nucleating agent to reduce super-cooling effects. They have added clays to stop the separation of liquid and solid and, most importantly, researchers have been able to lower the melting point by the addition of sodium chloride and/or aluminum chloride. These modifications have resulted in a promising thermal storage material that has a melting point of 55°F and is stable after cycling.

This optimized eutectic salt has a heat capacity of 50 BTUs per pound. This reduces to 35 BTUs per pound of latent heat and 15 BTUs per pound of sensible heat for a 30°F temperature change. The melting point of 55°F can be reduced to 45°F, but a penalty is incurred in the latent heat capacity. The values given above are representative of the material after it has been stabilized by 100 cycles of freezing and thawing.

The density of these salts averages about 100 pounds per FT^3, compared to 57 pounds per FT^3 for ice. The higher latent heat capacity of ice (144 BTU/pound) negates the density advantage of the salts in terms of storage volume. For example, the minimum volume required to store 3×10^6 BTUs (250 ton-hours) is as follows:

<u>For ice</u> $$\frac{3 \times 10^6}{144 \times 57} = 375 \; FT^3$$

<u>For eutectic salt</u> $$\frac{3 \times 10^6}{35 \times 100} = 857 \; FT^3$$

Modified eutectic salts are available today in limited quantities from a few research laboratories. One source for the low temperature salts is the Institute of Energy Conversion in Wilmington, Delaware. The Institute has borrowed packaging technology from the food industry and has packaged the material in low cost "sausages" which are 20" long and 2" in diameter. Each sausage is wrapped in high density polyethylene, and weighs 3 lbs. The projected cost of these storage devices, assuming full scale production, is 15 cents a pound plus shipping costs. Therefore the basic storage cost for a small commercial building (about 250 ton-hours) would be over $20,000. For this reason, eutectic salts are not a good choice for AC-TES projects at this time. Also, the 55°F melting point of the salt will not allow for proper humidity control in the conditioned space because the air temperature would be too high to condense much moisture out of the airstream. While it is possible to formulate the salts with a 45°F melting point, the loss of latent heat capacity would require more pounds of salt for a given capacity. The volume required for storage would increase and the cost of storage would be even higher than for the 55°F material.

To summarize the outlook for phase-change chemical storage--this concept is still in the development stages but has good potential for the future. This type of chemical storage should consume about the same cooling energy per daily cycle as a chilled water system because the condensing temperature is about the same. Phase-change chemical storage should have about a three-to-one volumetric advantage over chilled water systems. At present, the primary disadvantage is the high cost of the salts. Perhaps with additional research, the cost per pound can be reduced and the thermal characteristics can be improved to the point where this type of storage will become economically competitive.

OPTION 4 - Freon Accumulator

The freon accumulator option is still in the conceptual stage, but it is a concept that is worthy of further development. There is no evidence in the technical literature that this method of storage has been tested on the residential or commercial scale. As indicated in Figure 3, this approach requires a relatively simple modification to a conventional DX freon system. This is the simplest of all possible storage

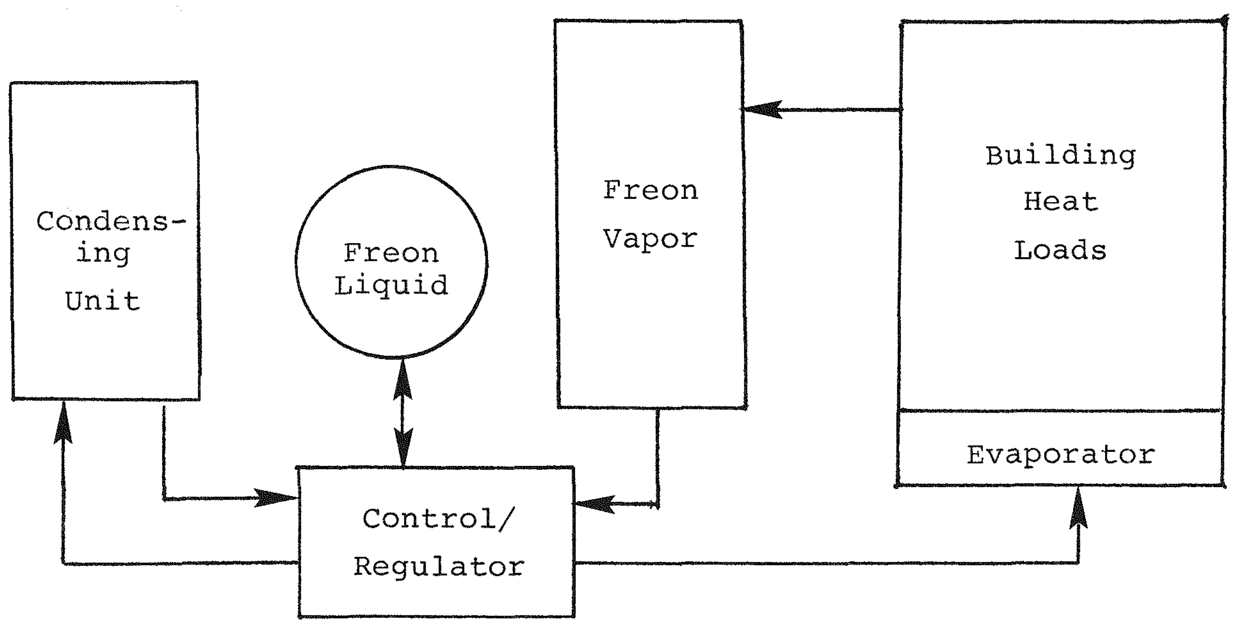

FIGURE 3. Freon Accumulator Concept

systems. This concept involves placement of a set of control valves and a pressure regulator in the liquid line between the original condensing unit and the evaporator. During off-peak hours the excess high-pressure liquid freon from the condenser is stored in a liquid holding tank for use during on-peak hours.

One disadvantage of this system is that a large volume of low-pressure freon is produced by the evaporator during on-peak hours. This vapor must be stored temporarily in a low-pressure holding tank before being condensed and returned to the liquid freon accumulator. Vapor storage volume requirements could be reduced with a partial compression stage between the evaporator and the vapor accumulator. However, this would require some on-peak power for compression. Also, if the refrigerant was mixed with a lubricant there would be a tendency for the freon and oil to separate in the vapor storage tank. These problems must be considered in any future development work.

The other disadvantage is that 250 ton-hours of storage would require about 40,000 pounds of freon (500 cubic feet of liquid R22). Even though this volume is relatively small, the wholesale cost of this much freon at today's prices would be about $18,000. The advantage of this system for retrofit application is that a new condensing unit and hydronic coil are not required. The modification requires only the addition of two storage tanks and the control/regulator.

The energy consumption per ton-hour of storage for the freon accumulator should be the lowest of the options considered in this report. This results from the fact that there are no heat transfer barriers in the evaporator (chiller barrel, ice buildup) and the pumping requirements are minimal compared to the other three options. The estimated performance of this concept is also listed in Table 2 below.

TABLE 2. Results of Preliminary Evaluations

Type of System	Condenser Energy KWH/Season
Standard DX Rooftop Unit	43,513 KWH
Option 1 - CW-Carrier 38AE044	35,839 KWH
CW-Carrier 38AD024	34,718 KWH
Option 2 - Ice-Carrier 38AE054	41,341 KWH
Ice-Carrier 38AD034	40,640 KWH
Option 3 - Phase-Change Chemical Storage	approx. 36,000 KWH
Option 4 - Freon Accumulator	approx. 33,000 KWH

The results of the preliminary evaluation of the four options can be summarized as follows:

Chilled Water - Excellent energy efficiency, uses mostly conventional HVAC components, poor volumetric efficiency, technically feasible, economic feasibility looks favorable for the future.

Ice Storage - Good energy efficiency, uses mostly conventional HVAC components, excellent volumetric efficiency, technically feasible, economic feasibility looks favorable for the future.

Phase-Change Chemical Storage - Good energy efficiency, uses storage media that is only available at present from research laboratories, good volumetric efficiency, technically feasible, economic feasibility is questionable for the future.

Freon Accumulator - Excellent energy efficiency, uses conventional HVAC components, can use original condensing unit, very poor volumetric efficiency (unless two-stage compression is used), technically feasible, economic feasibility is questionable for the future.

For the reasons listed above, it was decided to devote the rest of this study project to the evaluation of specific problems and opportunities related to chilled water and ice storage systems. In addition, it was determined that these further evaluations should be directed toward applications of approximately 30 tons of peak cooling capacity. This size was selected because single and multiple units of this capacity are used throughout the expanded commercial sector today.

2. REPORT ON PHASE I ACTIVITIES

A. OVERVIEW OF PHASE I AND PLANS FOR PHASES II AND III

The AC-TES project was originally conceived as a three-phase program, with a major decision point at the end of Phase I. The purpose of Phase I has been to explore the technical and economic feasibility of converting existing commercial buildings to the use of thermal storage air conditioning. The question to be answered at the end of the first phase is "Will the demonstration of a commercial-scale AC-TES system help promote wider use of this energy-saving concept?"

The technical feasibility of thermal storage air conditioning has never really been in doubt, because chilled water and ice storage cooling systems have been in use for more than 40 years. However, the "technical feasibility" questions for this project has been directed more toward developing a system concept that operates on a daily cycle. In addition, the new commercial concept should gain efficiency from the use of nighttime air for condensing of freon and it should take full advantage of "off-peak" rates that are beginning to be offered by electric utilities.

What has emerged from Phase I investigations is the fact that AC-TES systems for commercial applications can be constructed from components that are available "off the shelf". The condensing units, pumps, valves, and storage tanks that are used for other applications can be easily adapted to the AC-TES system concept.

The one exception to this "off the shelf" adaptability is in the area of electronic controls. In order to make standard HVAC components function efficiently on a daily cycle, a relatively sophisticated controls package will be required. The controls package can be constructed from standard components, but the internal design and the manner in which it interfaces with mechanical components, building operating cycles, and the rate structure will require very careful consideration by the design engineer. Only by careful analysis of all time-based variables can the design engineer achieve a system which will produce maximum energy savings, maximum demand savings, and a minimum economic payback period.

Phase I Activities

The activities which have been accomplished during the first phase of this project are shown in Figure 4. This PERT Chart indicates that the project began in July of 1980 with several parallel activities: a detailed study of "time of day" rates, performance analyses of various TES concepts, and the selection of a demonstration site. Next, the performance of the baseline system (standard rooftop DX) was compared to the performance of chilled water and ice storage systems. These comparisons were made for systems that were matched to the demonstration site. Detailed discussions of these analyses are given in Chapter 3.

Based upon these calculations, it was determined that a chilled water storage system would be best for the selected site. Therefore, a preliminary system design and specifications

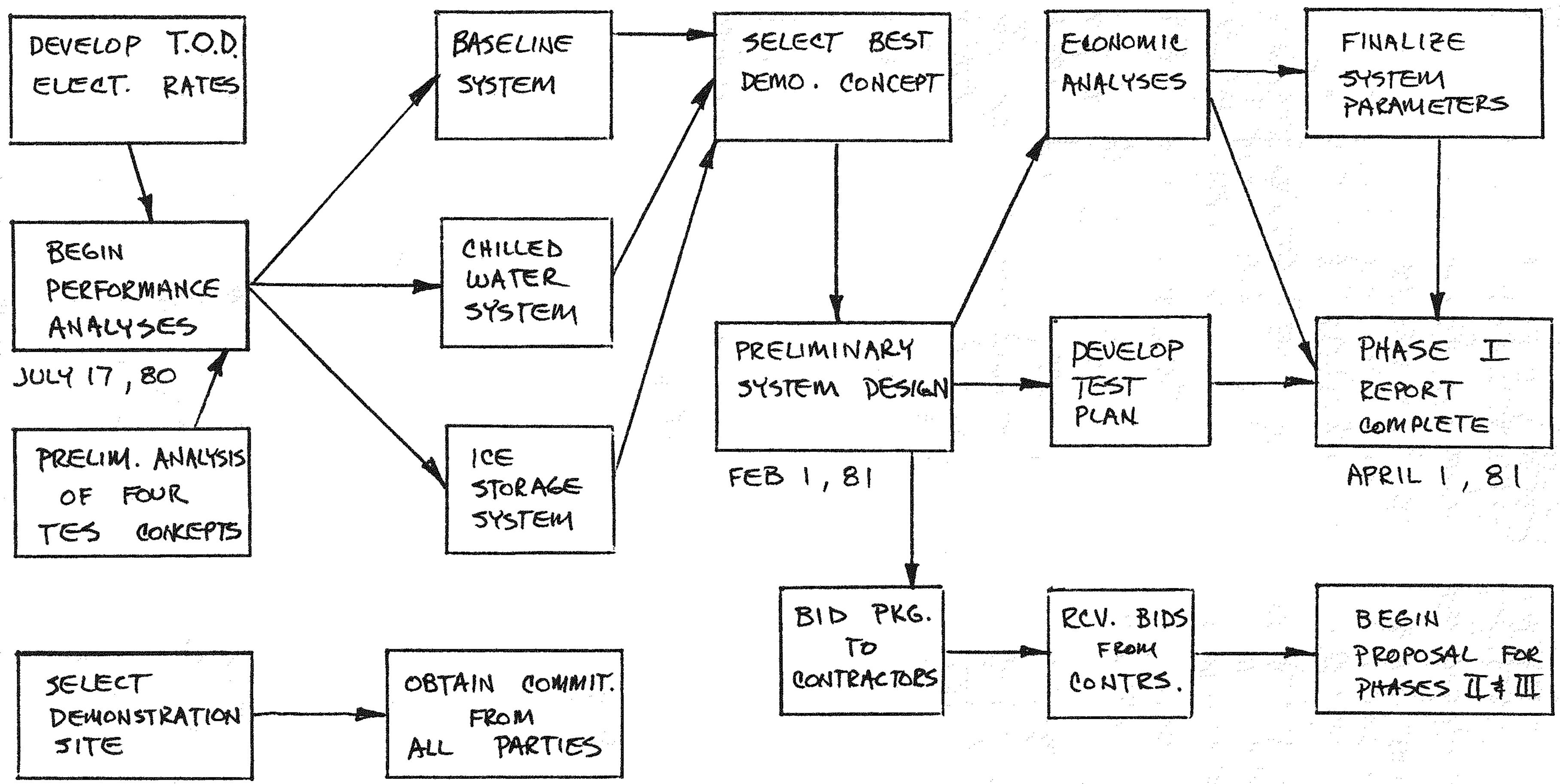

FIGURE 4. PHASE I PERT CHART

were developed in preparation for sending out a bid package to contractors. Tentative commitments were obtained from the owner of the test site building (the Orzech-Brady Group) and from the major equipment sponsor (Lennox Industries).

Four prominent Dallas-based HVAC contractors were asked to bid on the construction work for Phase II. These contractors were Dring Engineering, American Air Conditioning, United Air Conditioning, and Ace Furnace. All four of these firms have extensive experience in small-to-medium sized commercial installations. The quotation information received from these contractors is summarized in a separate document, which is the proposal to TENRAC for Phase II and III demonstration and testing. Phase I has been concluded with the preparation of a test plan, the tabulation of economic and performance data for the ice and chilled water options, and a "review briefing" for all parties connected with Phases II and III.

Plans for Phases II and III

Plans for the construction and testing phases are shown in Figures 5 and 6. Assuming that TENRAC approves funding for Phases II and III, the construction phase will begin on September 1, 1981. First, the contractor proposals will be evaluated and the most qualified firm will be selected. The contractor will review the design developed during Phase I and complete a set of working drawings for the installation at the test site.

In parallel with the design documentation, the equipment sponsor will begin fabrication of the chiller/condenser unit. Also, DP&L will review the test plan and work with BYWATERS &

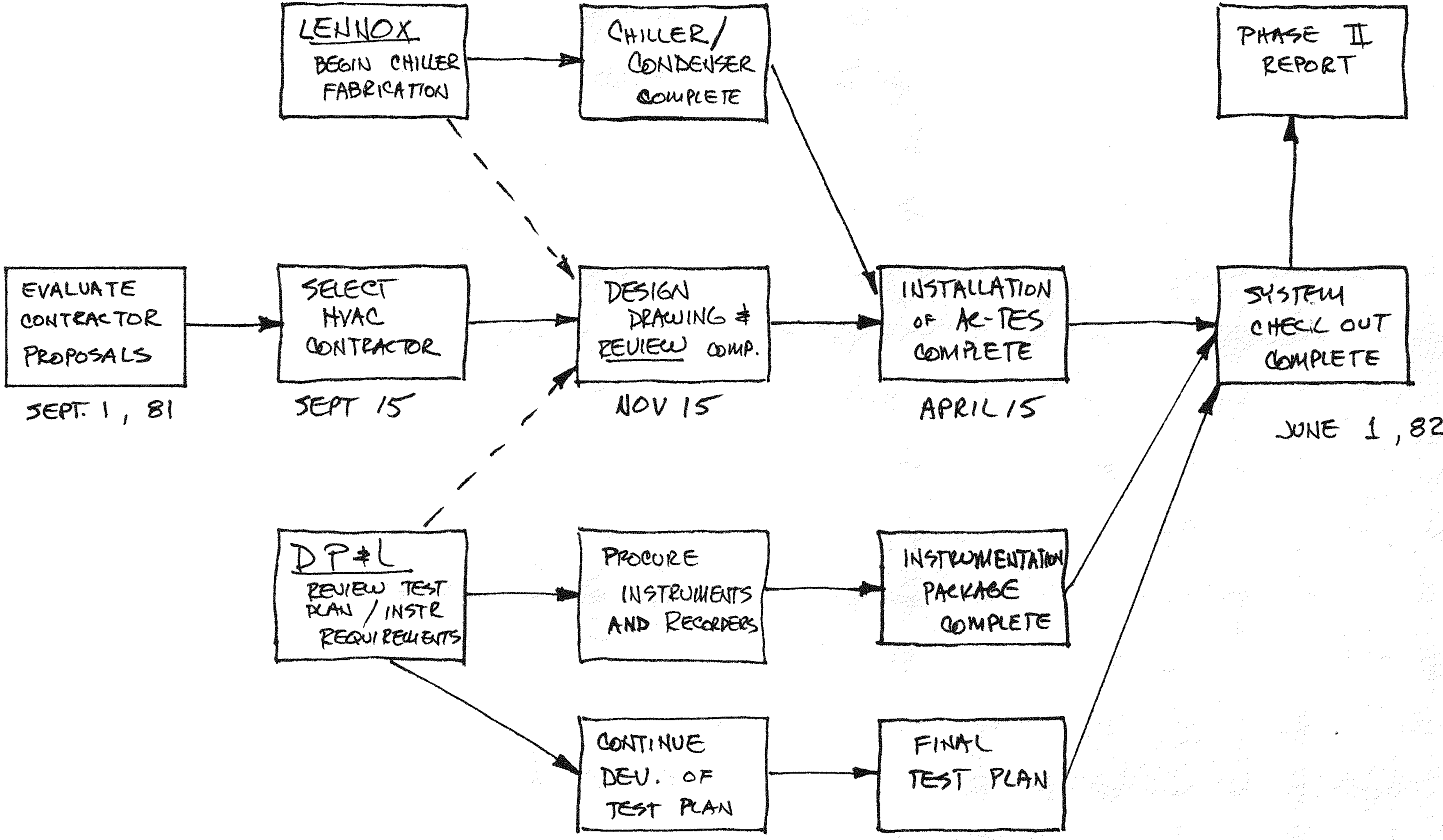

FIGURE 5. PHASE II PERT CHART

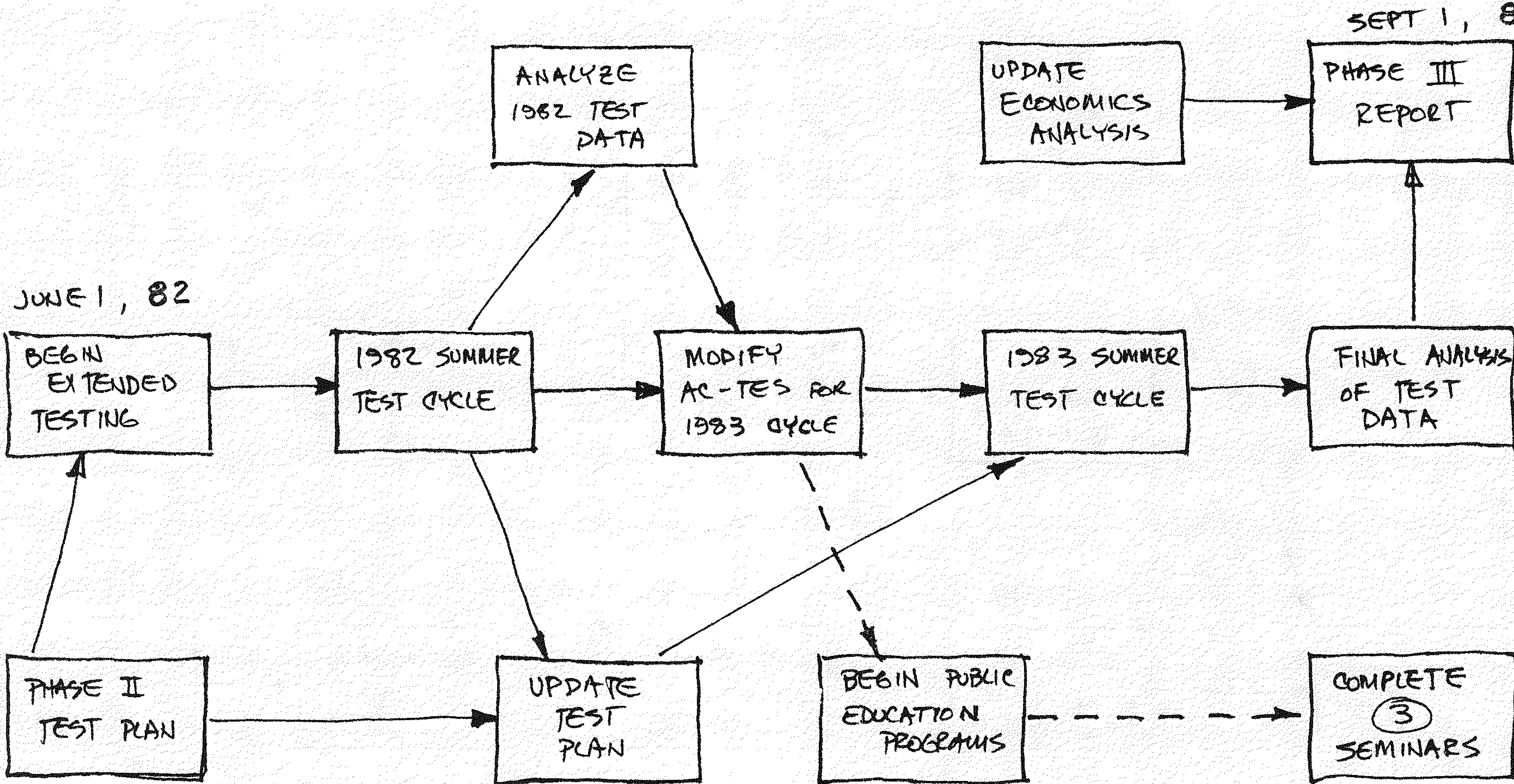

FIGURE 6. PHASE III PERT CHART

ASSOCIATES on selection and installation of instrumentation. A major design review will be held on about November 15 in order to finalize all design details, and get the "go ahead" approval from the building owner. The remainder of Phase II involves overseeing the installation and checkout of the AC-TES system. Final checkout and completion of Phase II is scheduled for June 1, 1982. This will allow testing of the system for most of the cooling season for 1982, and most of the 1983 season.

Phase III is defined as the extended testing period from June 1, 1982 to September 1, 1983. This phase begins by operating the system in accordance with the test plan which was developed during Phases I and II. At the conclusion of the 1982 test cycle, experimental data will be analyzed and the test plan for the 1983 test cycle will be adjusted accordingly. Modifications to the test plan will include changes to mode of operation, start/stop timing, and any other operational changes that would enhance the energy and cost saving features of the AC-TES concept.

Assuming the first test cycle is successful, then BYWATERS & ASSOCIATES will submit a proposal to the Conservation Division (Educational Programs) of TENRAC to offer technical seminars on the AC-TES concept. The goal of this public education program would be to hold three seminars (Dallas, Houston, and San Antonio) in order to promote the wider commercial use of thermal storage air conditioning. Local utility companies would be asked to co-sponsor these seminars.

Phase III would be concluded with a detailed analysis of all test data taken over two seasons of testing. A final report would be prepared for TENRAC that would draw conclusions in three key areas:

(1) Technical feasibility of the AC-TES concept.

(2) Economic feasibility and implications for future TOD electric rates.

(3) Strategies for encouraging owners of commercial buildings to adopt the AC-TES concept.

B. ANALYSIS OF TIME-OF-DAY RATES

As previously mentioned, there are two basic economic incentives for the owner of a commercial building to convert to an AC-TES system.

(1) Energy and cost savings due to efficient night-time condenser operation.

(2) Cost saving due to rate structure features which allow lower KWH charges for off-peak consumption of electric energy.

The family of electric rates which provide special off-peak benefits are usually referred to as "TOD" or "TOU" rates. TOD stands for time-of-day, and TOU stands for time-of-use. These types of rates are now being developed and implemented by many electric utilities across the United States. State and federal regulatory agencies are also exerting pressure on utilities to accelerate the introduction of optional TOD rates. In some states mandatory TOD rates are being considered as an incentive for both demand and energy conservation.

The implementation of "time of day" rates is closely tied to the desire of many electric utilities to make all rate structures reflect the true cost of service for each class of customer. TOD rates complement the "cost of service" philosophy because they usually produce a more equitable chargeout of capital costs than do conventional rates which are time-independent. This is true because utility capital requirements are dictated by peak load requirements. For utilities in Texas, this peak demand usually occurs during the mid-afternoon hours of July, August, or September, and is a direct result of the pervasive use of air conditioning.

Therefore, electric power customers who can minimize or eliminate their mid-afternoon KW demand by the use of thermal storage air conditioning, or other demand control methods, should not have to pay the full capital charge or demand charge which is contained in conventional declining-block rates. In fact, some rate analysts argue that off-peak power should be sold at rates which approach the fuel cost. In theory, off-peak power might sell for only 1/3 or 1/2 the cost of power sold on normal rates, since fuel costs typically represent between 30% and 50% of the total cost per KWH. If a particular TOD rate structure was designed to include a 2-to-1 or 3-to-1 premium for on-peak power consumption, then the peak-to-off-peak cost ratio (per KWH) might be 7-to-1 or greater.

It is also important to note that the Federal Government is gathering data on marginal generation costs under the terms of PURPA (Public Utilities Regulatory Policy Act of 1978). Section 133 of this law requires utilities to submit hour-by-hour generation costs and projections of future time-of-day costs. Ultimately, DOE and other state utility commissions will probably use this information to encourage the wider use of TOD rates. Within the utility industry, the Electric Power Research Institute (EPRI) is conducting feasibility studies of TOD/TOU rates. A brief progress report on the acceptability of these rates is given in the December 1980 issue of EPRI Journal, reference [3].

Several existing TOD rate structures were reviewed as part of the Phase I economic studies of AC-TES concepts. These rates are now offered by several electric utilities on an "experimental basis". Two of these experimental TOD rates are shown in Figure 7. The Gulf States TOD-EX rate is fairly typical of those now being offered in Texas. This rate has three time steps: off-peak, intermediate peak, and on-peak. The ratios of the steps to off-peak power are approximately 2-to-1 and 4-to-1. The Texas Electric Service rate "RX", also shown in Figure 7, has step ratios of about 2-to-1 to 6-to-1.

Based upon a review of these and other TOD rates, it was decided to develop two time-dependent rates which were representative of today's rate-making philosophies, which could then be used to analyze the economic merits of the proposed commercial AC-TES system. The two rates which evolved from these considerations are shown in Figure 8. They are two-step

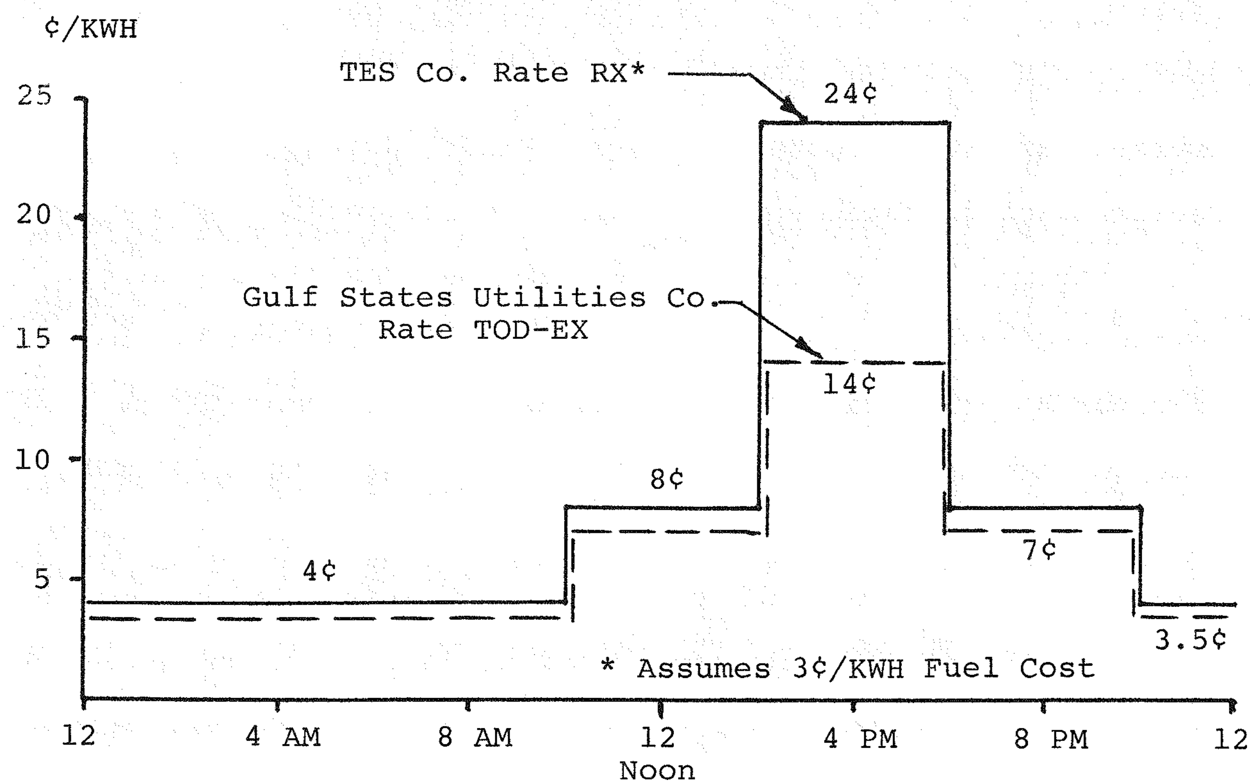

FIGURE 7. EXPERIMENTAL TOD RATES

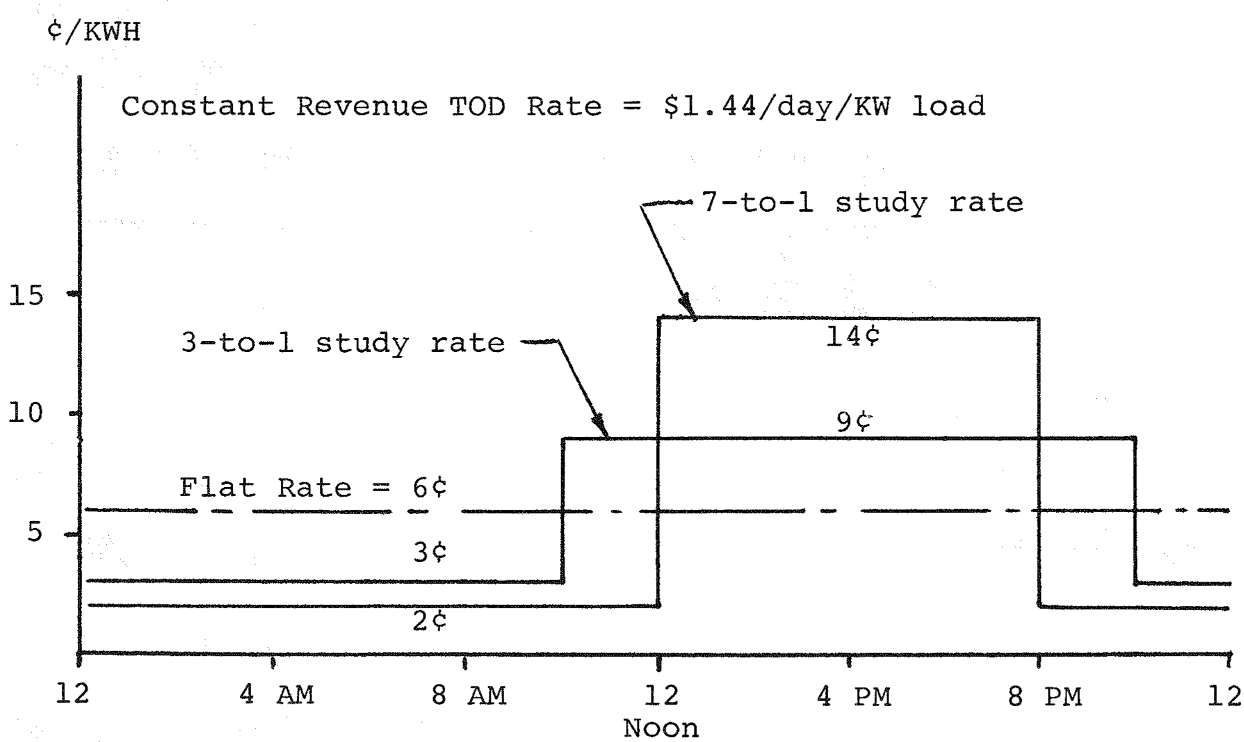

FIGURE 8. RATES USED IN ECONOMIC ANALYSES

rates which reflect acceptable cost levels, relative to a typical commercial rate for the 1981-82 time period. This typical rate was selected as 6¢ per KWH, and the effects of declining-block rate structure have been neglected. The two TOD rates which were selected for later economic analyses are designated "3-to-1 study rate" and "7-to-1 study rate". Each of these hypothetical TOD rates is designed to produce the same revenue as the 6¢ per KWH flat rate, assuming a constant load was operating for 24 hours each day. The constant revenue rate for the flat rate and the two study rates is $1.44 per day per KW. The 3-to-1 study rate considers a 12 hour on-peak period from 10 AM to 10 PM. The 7-to-1 study rate considers a more likely 8 hour period from Noon to 8 PM.

Another important factor for commercial electric customers to consider is the meter connection for TOD service. If a commercial customer is going to install a thermal storage air conditioning system, it will usually produce maximum savings if only the condensing unit (water chiller or ice maker) is connected to the TOD meter. The fan motor, water pumps, electronic controls and all usual building loads should be connected to the original meter which is billed on normal rates. This method of connection will usually provide the maximum financial gain because it places all daytime loads on the original meter, which has only moderate penalties (demand charges) for peak daytime consumption.

If all electric power was routed through one TOD meter, the penalty (3-to-1, 7-to-1, etc.) associated with the "on-peak" consumption of lights and other normal daytime loads would probably offset the saving gained from operating the condensing unit during "off-peak" hours. This effect is particularly true for typical commercial buildings where the annual KWH energy for comfort cooling is less than half the total KWH consumption.

If for any reason the air conditioning energy fraction is 60% of the total annual KWH or greater, then a single TOD meter or a single normal meter may be best. The most economical solution to the metering option will depend upon the air conditioning energy fraction, the nature of available TOD and normal rates, and the operating characteristics of the building in question. Building owners who are considering thermal storage air conditioners are encouraged to explore several rate options and meter options with the assistance of the rate expert at their local electric utility.

Some utilities may balk at the idea of allowing a customer "to divide" electric service into two metered accounts where a selected off-peak load is connected to the TOD meter. However, there appears to be no legal precedent for a utility refusing to divide electric service into two or more accounts. Of course, the utility would have the right to collect a special fee for the installation of the TOD meter, and to charge a second "customer service" fee for handling a second account. These additional fees should not be significant when considering the overall energy and cost saving associated with operating an AC-TES condensing unit on a separate TOD meter.

C. DEVELOPMENT OF A TEST PLAN

One of the most important activities that was completed during Phase I was the development of a preliminary test plan for use during Phase III. The purpose of this test plan is to clearly identify the procedures and test equipment necessary to evaluate the energy savings potential of the AC-TES concept. The test plan described in this section is identified as "preliminary" because it is expected that improvements in testing procedures will become apparent during completion of design details during Phase II. Also, major modifications to test procedures may become apparent at the end of the first test cycle during Phase III.

The preliminary test plan is summarized below as a seven-step procedure:

(1) Implement M & O's

Prior to recording of any test data, it is recommended that the building owner should implement basic maintenance and operating procedures for the existing HVAC equipment, the air distribution system, and the electronic controls. These actions will ensure that the Baseline system is operating at nominal efficiency and that the comparative test data will be representative of typical system performance.

(2) AC-TES System Checkout

After the mechanical contractor has completed installation of the thermal storage system, a complete checkout of all components should be conducted by the project managers. Chillers, pumps, valves, limit switches, piping, storage tanks, and all electronic controls should be checked to see that their performance is in accordance with the system specifications.

(3) Stabilize Internal Loads

Every reasonable effort will be made to stabilize the internal load of the test site building for the duration of each test cycle. The building owner will be asked to see that lights, internal equipment, operating hours per day, and days of operation per week are as uniform as possible. Any significant deviation from standard operating conditions would be noted in the data log book for later use in data correlations.

(4) Begin Alternate Testing of AC-TES and Baseline Systems

The fundamental approach to determining energy savings of the AC-TES system is based upon alternate-week testing of the storage system and the Baseline system. This method allows for comparison of weekly KWH totals (AC-TES vs.

Baseline) after making corrections for variations in internal load and weather effects.

(5) Record Test Data

The key parameters for each test cycle and the required recording intervals are indicated below.

Ambient Conditions, T_{DB}, T_{WB}	hourly
Internal Conditions, T_{DB}, T_{WB}	hourly
Condenser Energy, KWH	weekly
Condenser Demand, KW	daily
Fan, Pump, Aux. Energy, KWH	weekly
Unavoidable Internal Load Changes	as required
Storage Tank Level, percent	hourly
Other System Operating Variables (chilled water temp., flow rates, etc.)	as required
(Optional) Coil Δh, enthalpy change	hourly

The main instruments required for this long-term comparative testing are:

- Multipoint temperature recorder (12 channel) with paper-tape printer
- Integrating KWH meters (two)
- Peak demand meters (one)
- Analog recorder with paper-tape printer for monitoring system operating variables

(6) Data Reduction and Analysis

The primary test data would be recorded over a three-month period for each test cycle. This would represent about 90 days of accumulated data, over 2,000 hours and about 20,000 data points. Data reduction and analysis will involve a careful review of ambient and load conditions in order to achieve a best match of data for the two systems. Once the best matches are identified, minor adjustment to the KWH totals for the AC-TES system will be made in order to compensate for remaining differences in ambient and load conditions. These data will allow the calculations of KWH savings for weekly totals and projected KWH savings for an entire season. Electric rates will then be applied to these performance parameters and the dollar savings will be determined for the AC-TES system, relative to the Baseline (rooftop DX) system.

(7) Mode Change/Repeat Testing

It is anticipated that two or more major changes in operating mode will be made to the AC-TES system during the extended testing of Phase III. The major mode change which requires investigation is the change from a

12 hour "on-peak" rate period to an 8 hour "on-peak" period. Other mode changes which may be tested are alternate capacity/run-time combinations, and weather prediction used to establish the fill level in the storage tank. These alternate modes would require the test plan to be repeated for Steps (4), (5), and (6) above.

3. PERFORMANCE ANALYSES OF THREE SYSTEMS

A. BASELINE SYSTEM

The purpose of the Baseline system analysis was to establish a standard of comparison for the performance of the thermal energy storage systems. The Baseline system for this study was derived from the proposed test building, a single story office building located at 8617 Northwest Plaza Drive in Dallas, Texas. This building was carefully selected by the project investigators as being representative of a small commercial office building located in Texas. This building is known locally as the "Plaza Medical Building", and contains offices for about a dozen dentists and other medical specialists. It contains about 10,800 square feet of floor space and is cooled by a 35-ton rooftop DX unit.

The load dynamics of the test site air conditioner were simulated by the LOGIC 4000 computer program, which is licensed by Lennox Industries Incorporated. This program allows the design engineer to simulate the building's orientation, construction characteristics, internal loads, and weather conditions. It will compute the hour-by-hour cooling load and heating load for an entire year. Given the characteristics of a condenser, the program will calculate the daily KWH and yearly KWH consumption for both the condenser and the building. By careful matching of 1975 weather induced loads and internal loads, the project investigators were able to simulate the building's operation and to match its actual KWH consumption (from electrical bills) within a few percent.

The rooftop condensing unit on the test site building is a Carrier 06LA209500 unit, installed in 1964. The rated seasonal EER of this unit is 6.14 BTU/watt-hr. According to the Lennox Industries Marketing Department, a typical DX unit in Texas has a seasonal EER of about 6.5 Therefore, the investigators adjusted the Baseline system performance data upward to an EER of 6.5 to more accurately represent the condition of typical commercial DX units in Texas.

The test building presently operates from 5 AM to 9 PM Monday through Friday, and 5 AM until 12 Noon Saturday. For the computer simulation, the investigators adjusted the operational hours to 7 AM to 7 PM Monday through Friday and 7 AM to 12 Noon on Satuday. This condition is more representative of a typical commercial establishment. These two adjustments were incorporated in the LOGIC 4000 program and the seasonal KWH consumption was determined to be 116,379 KWH.

The Baseline system performance was also analyzed on an hour-by-hour basis for two representative summer days. These two types of days were defined as a "Worst Summer Day", or WSD, and a "Typical Summer Day", or TSD. The WSD closely matches the 97% probable "design day" condition defined in the ASHRAE Handbook of Fundamentals, 1977. Analyses of the Baseline system on the WSD allowed the investigators to study the performance of the standard air conditioning unit under peak load conditions. The TSD was developed from the statistical average of 30 years of weather data for Dallas County (developed in Reference [4]). By comparing the TSD heat load analysis to the seasonal heat load values (from LOGIC 4000), it was determined that the ratio of seasonal heat load to TSD heat load was 193. In other words, 193 days of typical load conditions is approximately equal to the system operating for the entire season under variable load conditions. This fact was later used to extrapolate TSD performance of thermal storage systems into seasonal performance data.

B. GRAPHICAL ANALYSES OF SYSTEM DYNAMICS

Hour-by-hour graphical analyses were used to simulate the performance of a chilled water system and an ice storage system. Each condenser and storage unit was sized to accommodate the dynamic heat load of the test site building. The performance of these systems was analyzed on a worst summer day (WSD) and a typical summer day (TSD). In addition, the chilled water system was analyzed for two different "on-peak" times, as defined by the hypothetical rates shown earlier in Figure 8.

The basic chilled water system configuration used for these analyses is shown in Figure 9. In this concept two parallel chillers are used to fill the supply tank during "off-peak" hours. During "on-peak" hours, only the blower and supply pump operate. An accumulator and check valve are used with a modulating chilled water valve to provide a constant supply air temperature from the main air handling unit. Other controls and limit switches are employed to make the system self-regulating. The basic control premise for this

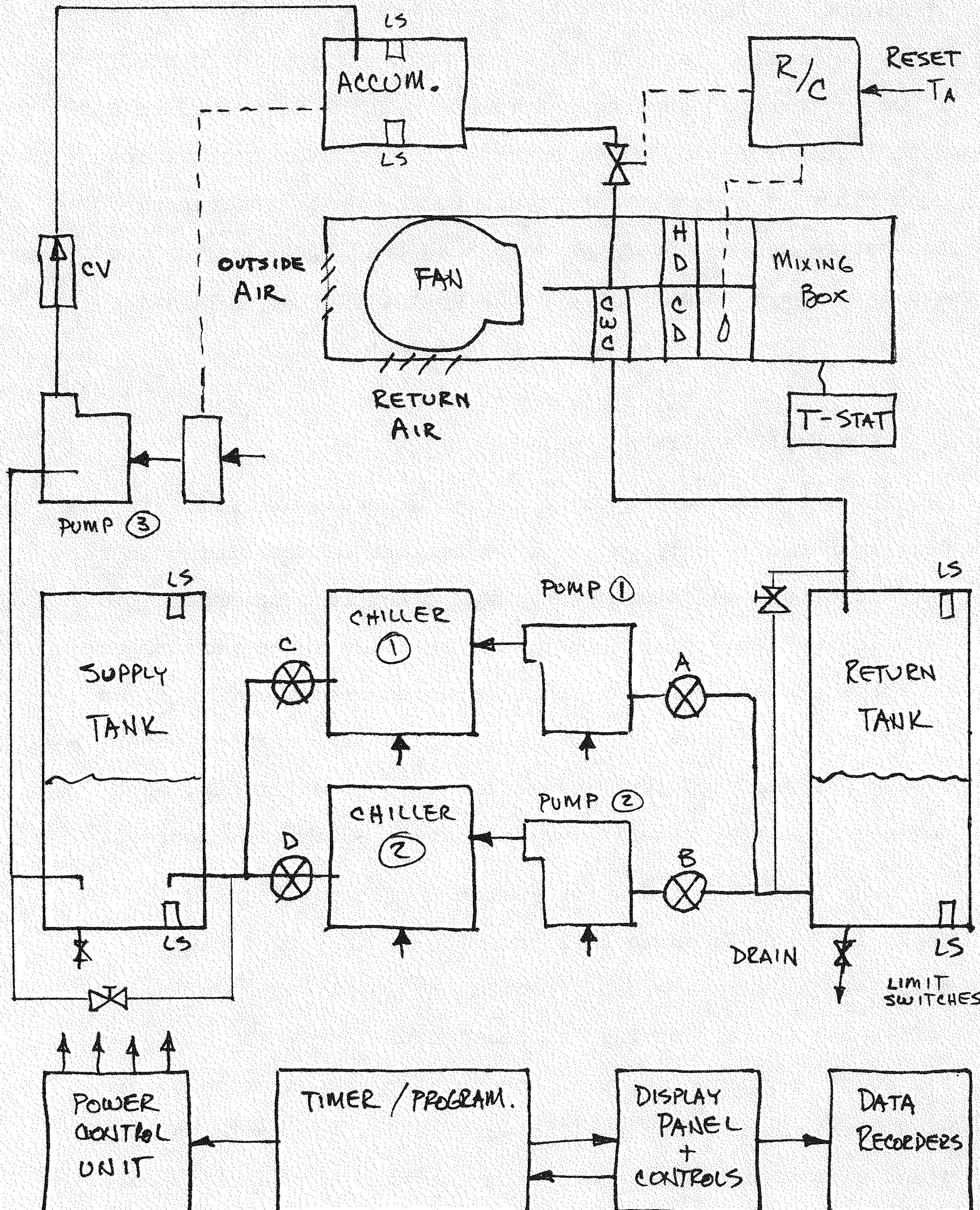

FIGURE 9. CHILLED WATER SYSTEM DIAGRAM

system concept is to start each day with a full tank of chilled water, and use only that volume of water necessary to meet the actual load for the day. The full tank volume is sized to handle the worst summer day load on the building, plus about 10% for system losses and design margins.

The graphical analysis of AC-TES dynamic performance can be explained by referring to the first analysis (Figure 10 - Page 48) and following the procedure listed below:

(1) Plot the hour-by-hour ambient temperature and the transient heat load on the same graph.

(2) For the assumed chilling equipment, plot the nominal cooling capacity (tons) at full load for the known variations in ambient temperature. Also plot the KW requirement of the chiller(s) for each capacity and temperature point.

(3) Beginning at the time of minimum ambient temperature, accumulate storage (area under the capacity curve) by going forward and backward on the time scale. Accumulate enough storage capacity (ton-hours) to handle the building load plus system losses and design margins. This graphical accumulation process determines the optimum start and stop times for "off-peak" operation of the chilling equipment by concentrating the condenser operation during the coolest hours of the night.

The graphical solution may require several iterations, depending upon the cooling capacity assumed and the defined "on-peak" period.

(4) Once a satisfactory accumlation sequence is determined (Step 3), the kilowatt-hours required for the chiller and transfer pumps can be determined by graphical integration under the KW curve. A separate power curve for the supply pump is used to determine its daily KWH consumption.

The key to this graphical technique is to carefully observe the variations of "capacity" and "power" curves with ambient temperature. Then, the analyst can adjust start/stop times and system capacity to achieve the necessary accumulated storage using the minimum electrical energy (KWH).

The four graphical analyses for chilled water systems are shown in Figures 10, 11, 12, and 13. Similar analyses were also plotted for an ice storage system operating on an 8-hour "on-peak" rate. A summary of the assumed variables and the graphical results for the chilled water system is listed in Table 3. The main summary of performance data for the Baseline, chilled water, and ice storage systems is given in Table 4. This summary shows the total energy consumed by the condenser and pumps for each type of system. Blower (air handler) energy is assumed to be the same for all of the systems. The daytime peak demand (KW) for each option is also listed in Table 4 to clearly show the load management benefits that come from AC-TES systems. Note that the daytime peak demand for the Baseline system is 44.7 KW, and the daytime peak demand for the storage systems is a maximum of 2.5 KW.

Seasonal energy requirements were determined from an earlier LOGIC 4000 analysis which indicated that a full cooling season was approximately equal in energy requirements to 193 typical summer days of operation. Therefore, the TSD data for each system could be extrapolated to cooling season energy requirement (far right column in Table 4). These analyses determined the energy savings potential (per cooling season) of three options, relative to the Baseline system (bottom of Table 4). The chilled water system, operating on a 12-hour "on-peak" period, used 38% less energy than the Baseline system. The same type of system, operating on an 8-hour "on-peak" period, used 40% less energy. The ice system, operating on the 8-hour period, saved 17%.

In each case, somewhat more than half of the energy savings was due to the fact that the Baseline system EER value was low (6.5) relative to the nominal value of EER for the storage system. The balance of the energy savings was due to the more efficient condensing action achieved by the nighttime operation of the storage systems.

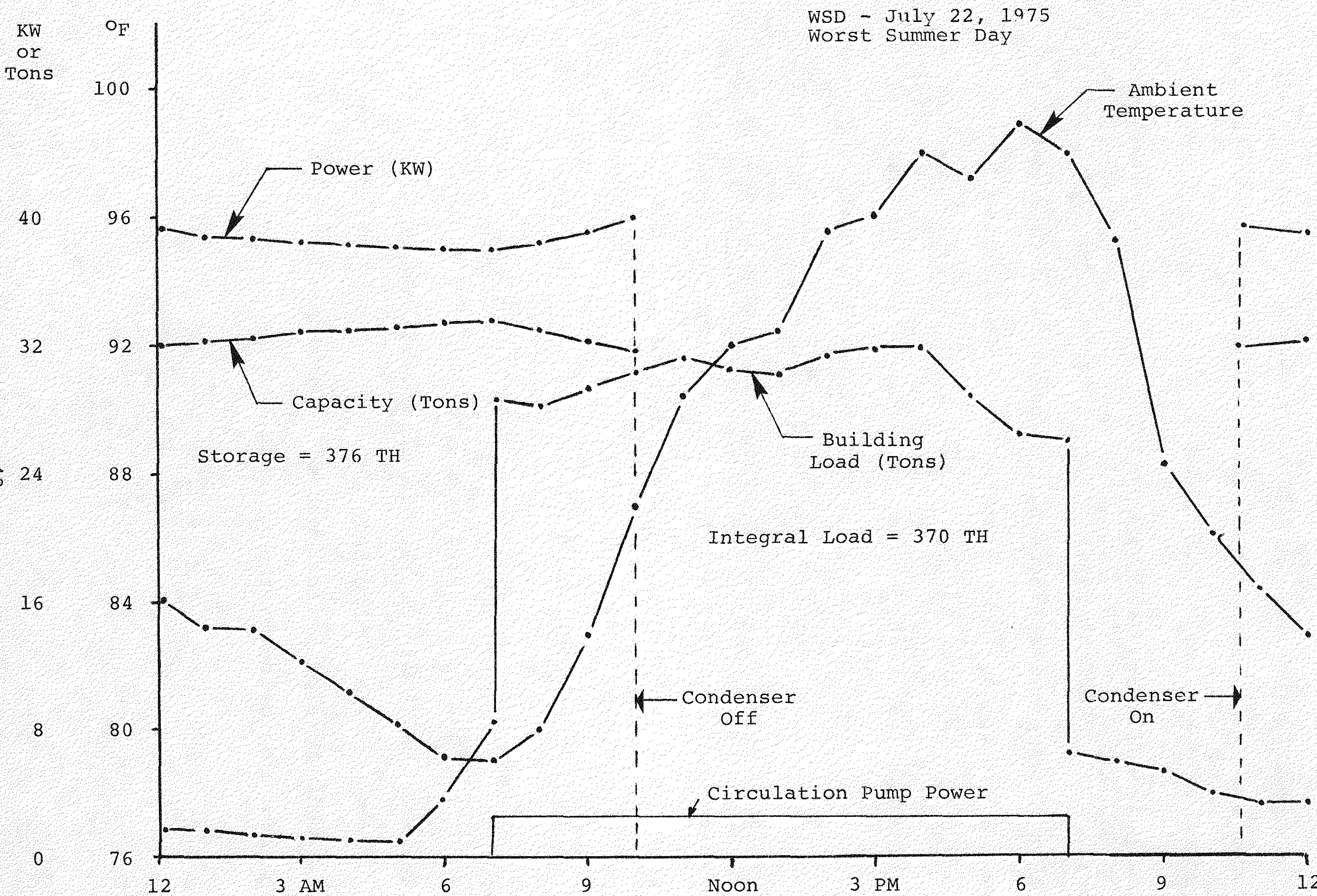

FIGURE 10. CHILLED WATER SYSTEM, WSD, 12 HOUR ON-PEAK

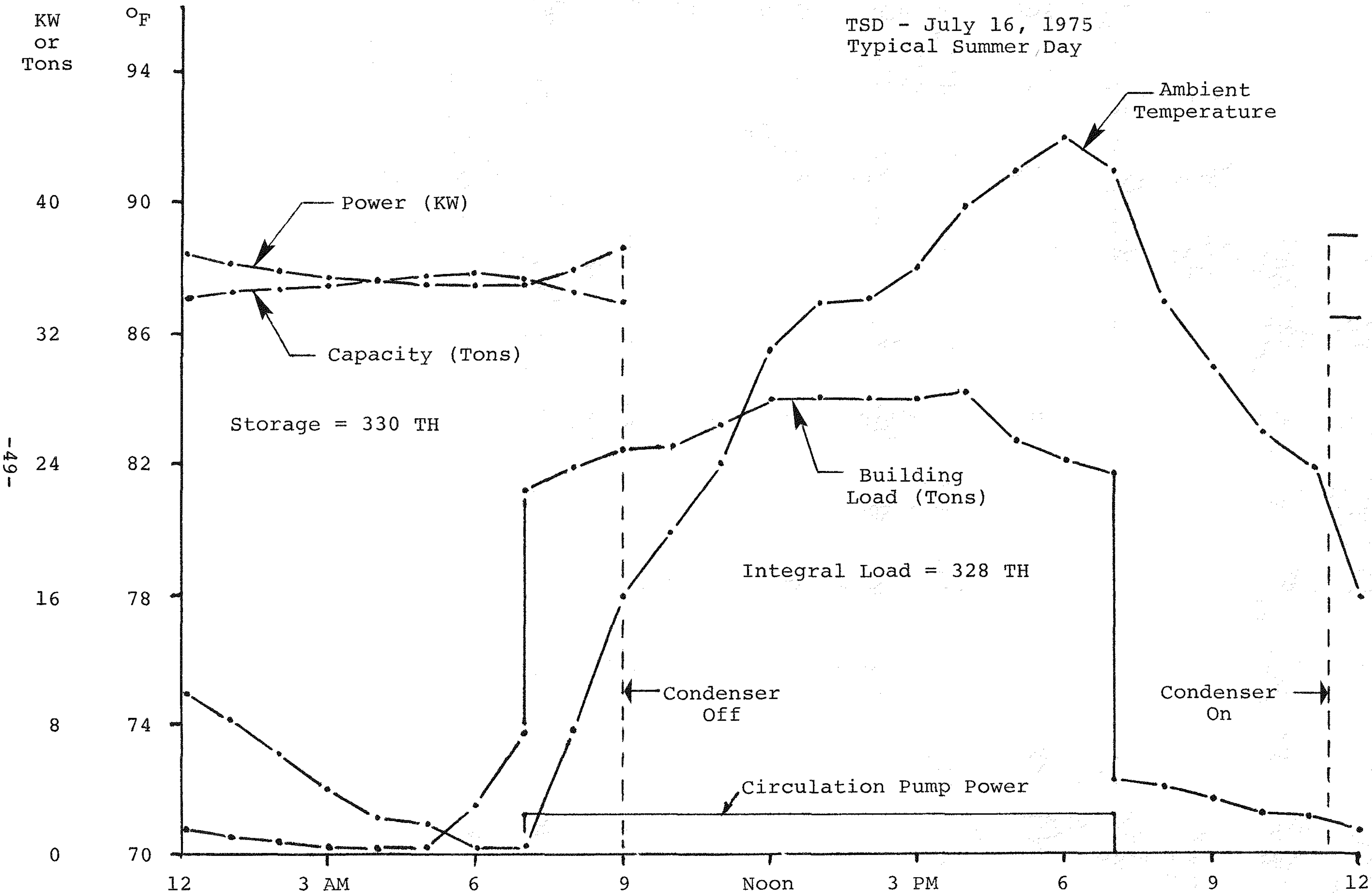

FIGURE 11. CHILLED WATER SYSTEM, TSD, 12 HOUR ON-PEAK

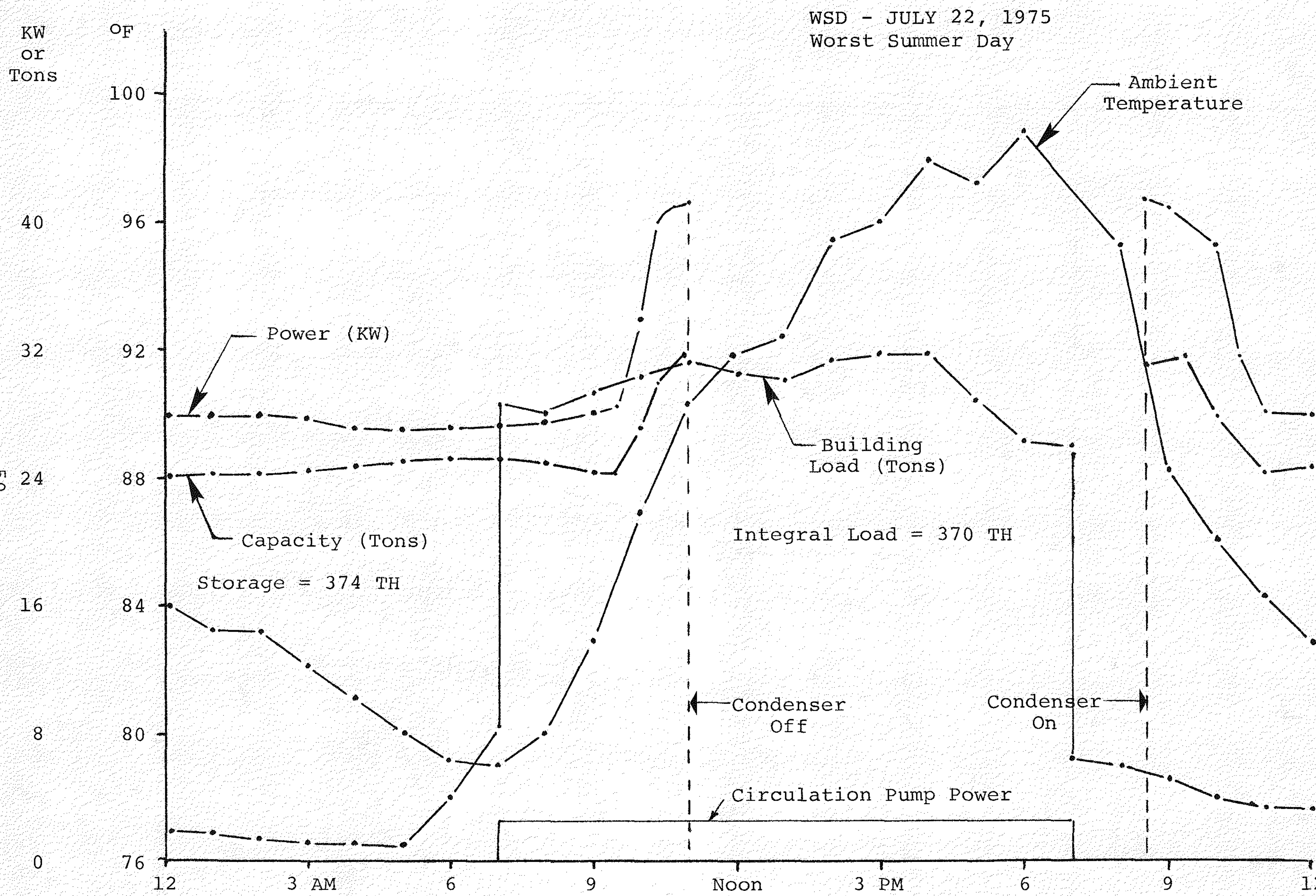

FIGURE 12. CHILLED WATER SYSTEM, WSD, 8 HOUR ON-PEAK

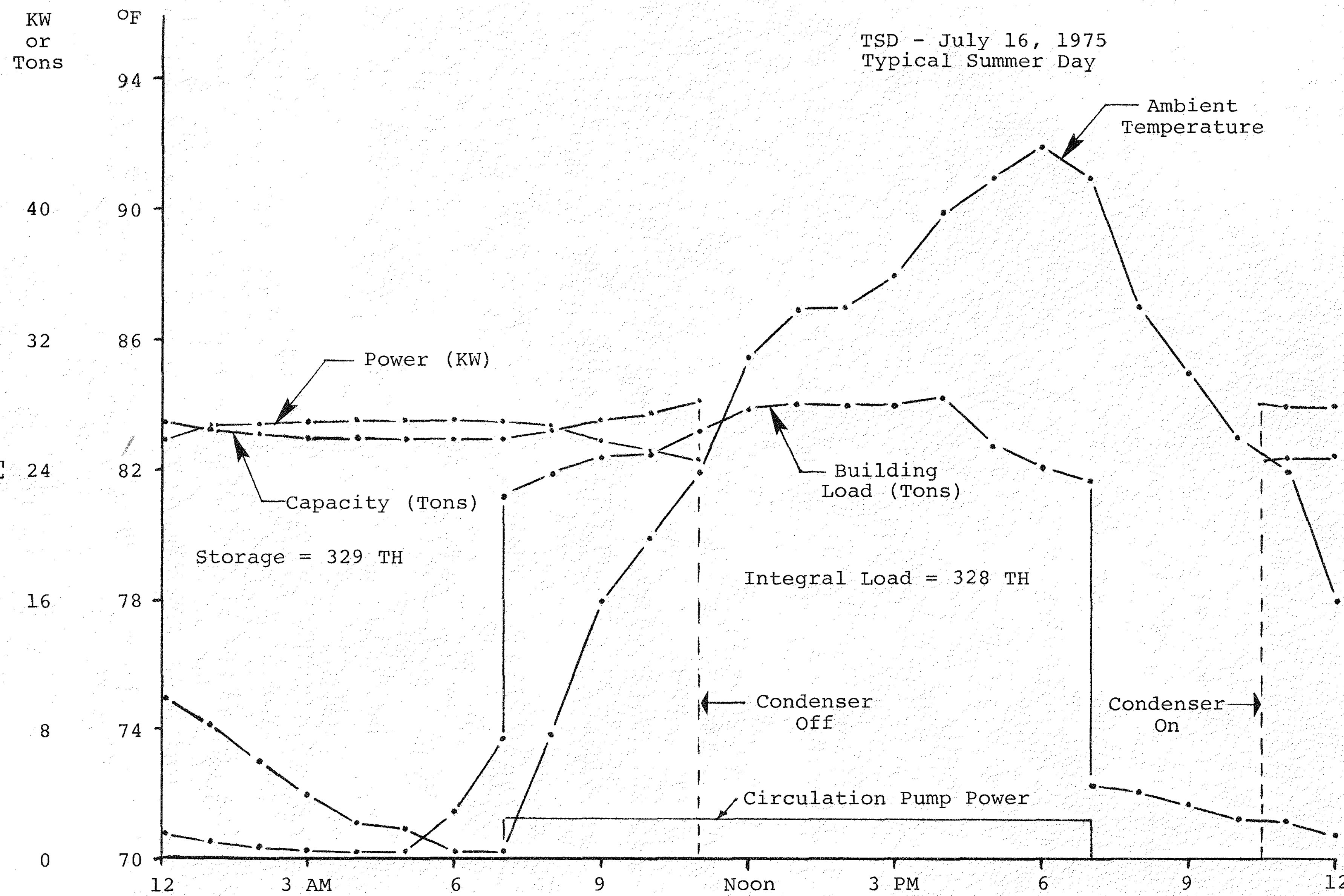

FIGURE 13. CHILLED WATER SYSTEM, TSD, 8 HOUR ON-PEAK

TABLE 3. GRAPHICAL ANALYSIS SUMMARY
(Chilled Water Storage Systems)

	Figure 10	Figure 11	Figure 12	Figure 13
Reference Page No.				
Condition	WSD	TSD	WSD	TSD
System	2-HS-7	2-HS-7	2-HS-7*	2-HS-7*
Bldg. Op. Time	7AM - 7PM	7AM - 7PM	7AM - 7PM	7AM - 7PM
On-Peak Time	10AM-10PM	10AM-10PM	12N - 8PM	12N - 8PM
Graphic Analysis Results				
Bldg. Load	370 TH	328 TH	370 TH	328 TH
On-Peak KW Max	2.5	2.5	2.5	2.5
Off-Peak KW Max	42.5	39.5	44.0	30.7
Accumulated Storage	376 TH	330 TH	374 TH	329 TH
KWH Consumed **	473	372	465	364
Condenser Run Time	10:30PM-10AM	11:30PM-9AM	8:30PM-11AM	10:30AM-11AM
Average Tons	32.7	34.7	25.8	26.3
Average EER	9.6	10.6	9.7	10.8

* Operating at Reduced Capacity (Lennox HS-7)

** Condenser and Pumps, no Blower KWH

TH = Ton-Hours

EER = Energy Efficiency Ratio (BTU/watt-hr.)

TABLE 4. RESULTS OF PERFORMANCE ANALYSES
(Condenser and Pumps)

System	WSD KWH	TSD KWH	WSD Daytime Peak-KW	Cooling* Season KWH
Baseline System				
(Rooftop DX) EER = 6.5	680	603	44.7	116,379
Chilled Water System				
12 hour on-peak rate	473	372	2.5	71,796
8 hour on-peak rate	465	364	2.5	70,252
Ice Storage System				
8 hour on-peak rate	676	500	1.8	96,500
Savings Summary				
Baseline - C.W.(12 hr.)	207	231	42.2	44,583
Baseline - C.W.(8 hr.)	215	239	42.2	46,127
Baseline - Ice (8 hr.)	4	103	42.9	19,879

SEASONAL ENERGY SAVINGS PERCENTAGE
(KWH Reduction Relative to Baseline System)

Chilled Water	(12 hr.)	38 %
Chilled Water	(8 hr.)	40 %
Ice	(8 hr.)	17 %

* LOGIC 400 analysis gives: 193 TSD (KWH) = Seasonal (KWH)

4. ECONOMIC ANALYSES OF THREE SYSTEMS

A. METHODOLOGY OF ANALYSES

The two critical economic factors for this study project were the assumed electric rate structures and the projected costs for converting a conventional commercial DX system into a thermal storage system. By combining probable values for these factors with the performance analysis data given in Table 4, the investigators were able to derive annual cost savings and simple payback estimates for each thermal storage option.

The first step in the economic analysis was to divide the cooling season energy for each system option into two components: (1) KWH energy that is consumed primarily in the on-peak period and billed at the assumed on-peak rate, and (2) KWH energy consumed off-peak and billed at the off-peak rate. This procedure was completed for four system options--Baseline, chilled water operating on an 8 hour on-peak period, chilled water operating on a 12 hour on-peak period, and an ice storage system operating on an 8 hour on-peak period. These divided energy components were then multiplied by the appropriate time-based rates, as specified in Figure 8, to arrive at annual operating costs for each option. Thus, the difference in operating cost between the Baseline system and each thermal storage option represented the annual cost savings for each option.

Next, the installed costs were determined for the three major AC-TES configurations, assuming labor and material costs for the 1981-82 time period. This is the same period assumed for the TOD rates developed in Section 2B and shown in Figure 8. Material cost estimates were based upon quotations from various vendors of HVAC components, with some allowance given for mass production of each item in the system. The most expensive component in each of the AC-TES systems was the storage tank. It usually represented slightly more than 40% of the total system cost. Next, in terms of cost, was the condensing unit at about 28% of the total cost; then in decreasing order of cost, installation labor, the water coil, electronic controls, control valves, and pumps.

The simple payback period was calculated for each option by dividing the annual cost savings into the total installed cost. It should be noted that simple payback does not include the effects of increasing utility rates or the time value of money as it relates to the first cost of each system. However, calculation of simple payback allowed the investigators to determine the relative economic merit of each system option.

B. COST SAVINGS/PAYBACK PERIODS

The results of the economic analyses are summarized in Table 5 on the following page. In most cases the cost data is shown for three storage system options and three electric rates (flat rate and two TOD rates). Some combinations of rates and assumed system storage capacity were not compatible.

TABLE 5. RESULTS OF ECONOMIC ANALYSES

	Baseline System	Chilled Water Storage System		Ice Storage System
Mode of Operation	Normal	8 hour	12 hour	8 hour
Installed Cost ($)	X	31,250	34,150	30,180
Flat Rate KWH/Season	116,379	5,790	5,790	4,246
Off-Peak KWH/Season	0	64,462	66,006	92,254
Optional Rate (See Fig. 8)	Annual Operating Cost ($/Season)			
Flat Rate	6,983	4,215	4,308	5,790
3-to-1 (12 hr.)	X	X	2,328	X
7-to-1 (8 hr.)	X	1,637	X	2,100
	Annual Cost Savings ($/Season)			
Flat Rate	Baseline	2,768	2,675	1,193
3-to-1 (12 hr.)	Baseline	X	4,655	X
7-to-1 (8 hr.)	Baseline	5,346	x	4,883
	Simple Payback (Years)			
Flat Rate		11.3	12.8	25.3
3-to-1 (12 hr.)		X	7.3	X
7-to-1 (8 hr.)		5.8	X	6.2

CONVERSION OF EXISTING CHILLED WATER SYSTEM TO AC-TES

Rate		
7-to-1 (8 hr.)	Conversion Cost	= $20,700
	Annual Cost Savings	= $ 3,215
	Simple Payback	= 6.4 yrs.

X = Not Applicable

These cases are indicated by an "X" in Table 5.

The maximum annual cost savings of $5,346 occurred for the chilled water system operating on the 7-to-1 study rate (8 hour on-peak). $4,883 in annual cost savings was achieved for the ice storage option on the 7-to-1 rate, and $4,655 in savings was obtained for the chilled water system on the 3-to-1 rate (12 hour on-peak). By combining these savings with the estimates for first costs, the payback periods were determined for each option:

Retrofit Option	Simple Payback
Chilled Water, 7-to-1 rate	5.8 years
Ice Storage, 7-to-1 rate	6.2 years
Chilled Water, 3-to-1 rate	7.3 years
Chilled Water/Ice, Flat rate	11 years +

One additional option was considered at the conclusion of the economic analyses. This option considers the conversion of an existing chilled water system to storage-mode operation on the 7-to-1 rate (8 hour on-peak). This conversion cost is substantially lower than other options considered because the water chiller is already in place; however, the annual cost savings are less than before because there is no opportunity to upgrade the EER of the condensing unit. The payback period for this option was calculated to be 6.4 years.

These analyses indicate that there is relatively little difference in payback period for ice storage and chilled water systems under the assumed conditions. Therefore, for commercial cooling systems in capacities around 35 tons it appears that other factors, such as available space and first cost, would dictate the choice between the options of ice and chilled water storage.

5. CONCLUSIONS AND RECOMMENDATIONS

Several general conclusions have been developed from the various performance and economic analyses conducted during Phase I.

- Retrofit applications of the AC-TES concept to commercial buildings with 35 to 50 tons peak capacity should have an economic payback of about 5 to 7 years, assuming TOD rates are available.
- Because of economies of scale in the storage and condensing units, larger commercial systems (200 tons and larger) should have payback periods of 5 years or less, also assuming TOD rates are available.
- In terms of minimum operating costs, chilled water storage will usually have a small advantage over ice systems for commercial applications. However, if availability of space in the retrofit building is a problem, ice storage will usually be the most logical choice.
- Chilled water storage systems should be considered for buildings that already have a central chilled water cooling system. Economical applications should exist for normal off-peak use and for extended operation in

lieu of expanded cooling capacity.

- The economics of operating an AC-TES system are extremely sensitive to the exact type of TOD rate which is available; however, shorter paybacks will be obtained for defined on-peak rate periods in the range of 6 to 8 hours.

- Widespread adoption of thermal storage cooling in the expanded commercial sector can reduce the peak demand on typical utilities in Texas by 20% or more. In addition, AC-TES systems can reduce cooling energy consumption by 10% and cooling costs by 50% or more---IF progressive time-of-day rates are offered by electric utilities.

Three basic recommendations have evolved from the work described in this report. If thermal storage air conditioning is to become a successful conservation and load management technique in Texas, the following items must be accomplished:

1. The Public Utilities Commission of Texas must encourage all electric utilities in the state to offer progressive time-of-day rates, with strong financial incentives for off-peak consumption of power.

2. The utility companies in Texas should take the lead in promoting use of the AC-TES concept, as part of their overall load management programs.

3. AC-TES testing projects should be sponsored by TENRAC and public utilities to demonstrate the energy and cost-saving benefits of thermal storage cooling. These demonstration projects can be used to refine the controls and test various operating parameters so that energy-saving effects are maximized.

This report would be incomplete without noting the irony of today's thermal storage technology. Commercial use of AC-TES seems to be stalled in "technological limbo" somewhere between the two parties it can most benefit--the utilities and the manufacturers of HVAC systems. Utility companies in Texas appear to be waiting on the manufacturers to offer a full line of thermal storage cooling equipment. On the other hand, the HVAC manufacturers seem to be waiting on the utilities to offer progressive TOD rates so there will be strong incentives to purchase thermal storage cooling systems. The project investigators believe that this stalemate situation can be resolved to the benefit of all parties by implementing the three recommendations listed in this section.

APPENDIX: TECHNICAL REFERENCES

1. "Potential for Energy Conservation in Texas", W. L. Cepeda, GEAC Report 77-001, April 1977

2. "An Evaluation of Technical Options for Off-Peak Air Conditioning Systems", R. P. Bywaters and D. G. Hannan, Center for Energy Studies, U. T. Austin, May 31, 1977

3. "Electric Utility Rate Design Study", EPRI Journal, December 1980, pp 50-51

4. "Investigation of the Conservation Potential of Residential Heat Pumps with Thermal Energy Storage", R. P. Bywaters, J. P. Holman, and M. E. Larson, TEAC Report EDF-013, July 1979

5. "Interest in Thermal Storage Starting to Blossom, say Mfgrs", article in Air Conditioning Heating and Refrigeration News, March 2, 1981, p 16

6. "Thermal Storage: Resisting Temperature Blending", R. T. Tamblyn, ASHRAE Journal, January 1980, pp 65-70

7. "Cooling Storage Assessment Study", Electric Power Research Institute, EPRI Report EM-468, May 1977

8. "Ice Storage Systems Spark Air Conditioning Savings", C. R. Kohlenberger, Specifying Engineer, March 1981 pp 56-61