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Capital Cost Estimates of Selected Advanced Thermal Energy Storage Technologies

Final Report

Arthur D. Little, Inc.

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ARGONNE NATIONAL LABORATORY
Energy and Environmental Systems Division

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CAPITAL COST ESTIMATES OF SELECTED ADVANCED THERMAL ENERGY STORAGE TECHNOLOGIES

Final Report

by

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prepared for

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CHAPTER 1

OVERVIEW AND CONCLUSIONS

1.1 Background

In response to the nation's need to conserve energy, a number of programs have been directed toward reducing our consumption of energy. An important part of these programs is the improved use of thermal energy storage (TES) systems. These systems can conserve energy in three ways:

(1) by increasing the efficiency of the device or process;

(2) by recovering energy that would normally be lost, and

(3) by providing a means for matching variable patterns of energy demand and availability, which are presently out of phase.

A number of programs have been devoted to developing advanced TES systems. Some of this work has been sponsored by the Department of Energy (DOE) and some has been conducted by industry. Because of the large number of programs and the range of possible uses for employing thermal storage to conserve energy, a number of potentially successful approaches are open to the DOE. However, the field is presently so crowded with candidates, that it is difficult to identify the most promising systems and applications. Therefore, a method was needed for evaluating these diverse technologies on a common basis so that priorities could be established for further research and development.

1.2 Objectives of the Study

The primary objective of the study was to provide DOE with a method for evaluating the first cost of diverse advanced TES concepts on a common basis. For a total sample of at least 20 baseline and advanced TES technologies, the methodology developed was to be applied in the calculation of actual cost and performance measures.

1.3 General Approach

- Selection of Reference Applications

We began this program by developing a classification scheme for the different uses of thermal energy storage. This scheme was developed by considering the different kinds of programs sponsored by DOE and by evaluating the various mechanisms of energy loss that were amenable to reduction by use of advanced TES concepts.

Work on the development of TES has focused on five types of application areas:

(1) electric power generation, with solar input in which TES is used to store energy for use during cloudy periods or at night;

(2) conventional fuel-fired electric power generation, in which TES is used to improve load factors;

(3) cyclic losses, in which TES is used to reduce losses that occur when devices start and stop;

(4) batch losses, in which TES is used to recover waste heat; and

(5) source/sink mismatch, in which TES is used to increase the efficiency of processes that are dependent upon ambient temperatures.

These have been applied variously to commercial processes, transportation, space heating and cooling, water heating, and generation of electricity. From the array of possible applications of TES and uses for the stored energy, the residential and commercial HVAC applications that consume significant amounts of energy were selected for detailed considerations. Applications for which advanced TES systems were costed are:

(1) solar hot air or hydronic space heating of residences using diurnal storage;

(2) solar space heating, cooling, and water heating of residences and small apartment buildings using diurnal and seasonal storage;

(3) solar cooling of residences with absorption air conditioners using diurnal storage;

(4) off-peak electric space heating of residences;

(5) off-peak electric cooling of residences;

(6) passive solar heating of residences; and

(7) community sized storage for cooling.

Baseline systems for these applications were also costed. In addition, for some baseline systems, relationships between storage capacity and cost were developed.

These applications in residential heating and cooling were selected because DOE is sponsoring other programs to analyze the costs of TES technologies applied to power generation and industrial energy conservation.

- Specification of Operating Characteristics and Baseline Systems

Before the performance of various advanced TES concepts could be compared, these technologies would have to be incorporated into systems designed to meet specific operating characteristics. Thus, for each reference application, specifications were developed for storage capacity, output rate, and output temperatures.

For each of the nine reference applications, baseline systems were defined incorporating current technology and practice. These provided the basis for comparison with the advanced TES technologies.

- Advanced TES Technologies

The advanced TES technologies currently being developed can be classified under three conceptual approaches to thermal energy storage. Within these approaches, twelve specific TES technologies were considered.

  - Chemical Heat Pump TES

Chemical heat pump TES systems store energy by using vapor-pressure differences to drive chemical reactions in different directions with the absorbing or releasing of heat. This is done by maintaining two reservoirs, each containing one of the storage system chemicals at different temperatures by adding or removing heat. Typically, during charging, heat is added to a high-temperature reactor separating the two storage media while heat is rejected from a low-temperature reactor while condensing one of the media. The energy released during charging can be used for space or water heating. Discharging the system is accomplished by cooling the high-temperature reactor while heating the low-temperature reactor until the vapor pressure of the condensed medium is greater than the vapor pressure of the combined media in the high-temperature reactor. The condensed media then evaporates and the vapor recombines with the higher temperature medium giving off heat. The energy removed from the high-temperature side is used for space or water heating. The energy added on the low-temperature side will come either from outdoors, in which case the system acts like a conventional heat pump, or from cooling building air, thereby providing air conditioning. These systems are applicable to a range of applications from residential to commercial.

Three advanced TES concepts based on chemical heat pumps were considered:

EIC Corporation: Methanolated calcium chloride is heated to drive off methanol, which is condensed to store energy.

Rocket Research: Sulfuric acid is concentrated by boiling off water which is condensed to store energy.

Martin Marietta: A proprietary ammoniated salt slurry is heated to drive off ammonia, which is condensed to store energy.

- Phase Change TES

Phase change systems are designed to store a major part of their energy content at a constant temperature. This is done by using materials that have a phase change temperature at a suitable level (e.g., space heating: 80°F - 150°F or space cooling: 32°F - 50°F). This is desirable for two major reasons. First, the volumetric energy storage capacity is likely to be better than sensible heat storage systems. Second, system efficiency is improved by minimizing the upper or lower temperature required for charging. These systems are primarily suited for residential or small commercial applications.

Seven advanced TES concepts based on this system were considered:

Dow: Salts which change phase at various temperatures are encapsulated in aerosol type containers.

Franklin Institute: A salt (trimethylamine) in a liquid is dissolved or crystallized by circulating an immiscible fluid.

University of Delaware: Glauber's salt mixtures are encapsulated in long sausage-like plastic cylinders.

Clemson University: A salt (sodium thiosulphate) in a liquid is dissolved or crystallized by circulating an immiscible fluid.

Monsanto Research: Cross-linked polyethylene undergoes a solid phase change.

Suntek: Calcium chloride is encapsulated in building blocks with an epoxy coating.

Brookhaven: Phase change materials are micro-encapsulated and mixed with concrete to make building blocks.

- Aquifer TES

This system involves pumping large amounts of heated or cooled water into aquifers (large areas of porous media underground) to store energy on a seasonal basis. Energy is removed by pumping the water out of the aquifer and passing it through heat exchangers. The energy to heat or cool the water comes from sources such as industrial or electric power plant waste heat, solar inputs, or from normal seasonal changes. These systems are suitable primarily for large-scale installations.

Two systems based on this concept were considered:

<u>DRI:</u> Water cooled by heat exchangers in Jamaica Bay off Long Island is stored in winter to cool JFK Airport in the summer.

<u>Texas A&M:</u> Water chilled by evaporative cooling is stored underground in the winter to provide cooling to a community in the summer.

In many cases these systems were only in the laboratory stage of development. Therefore, it was necessary to take laboratory systems and project them to complete systems incorporated into an HVAC installation suitable for the reference applications. With the cooperation of all the contractors involved, we were able to develop schematics that contained size and operating characteristics for the major elements of each system for each applicable reference application.

- <u>Definition of TES Module</u>

In order to provide an analytical framework for the cost and performance comparisons, three components of a TES system were defined:

(1) the input section consisting of components that collect energy and transfer it to the storage module;

(2) the storage module, including all components required to receive, store, and transmit the energy for use; and

(3) the application section consisting of all portions of the system required to extract energy from the storage module and pass it to the point of final use.

When the storage module is defined in this way, all circulation pumps and piping external to the basic storage system are considered part of the input or application section. Reference applications are defined so that both the baseline systems and the advanced TES technologies are based on the same heat-transfer methods. This means, for example that TES systems based on hydronic or liquid input and output are compared with a baseline system based on the same heat-transfer methods. Since the major differences among these systems are isolated in the storage module, a valid comparison can be made considering only that portion of the system.

Although the primary analysis was concentrated on the relative cost of the TES module per 10^6 Btu energy produced, some external hardware and operational parameters are affected by characteristics of the TES. In order to reflect the attendant cost differences, additional analysis was required concerning:

(1) the effect of high storage temperatures on solar collector costs;

(2) the effect of low storage temperatures on compressor first cost and operating costs; and

(3) the effect of chemical heat pump C.O.P. and collector temperature on storage size and collector area.

For each of these areas, cost differentials were developed for incorporation in the costing of the systems involving solar input or use of a compressor run off-peak to generate coolness for air conditioning.

- Estimation of Costs

The estimates in this report are generally equivalent to ex-factory costs. They include burden on labor but do not include manufacturers' margin on materials, which could add between 15% and 25% to the cost depending on the application. In addition, items which pass through a distributor and installer could add an additional 40% to 60% to the price paid by the end user. This comparison is clouded, somewhat, by the fact that some systems are site- erected while others are factory-assembled. However, when comparing costs within an application, this difference can be ignored. The methodology for making these cost estimates is described below.

Cost estimates were derived for each TES system application and baseline case to reflect the costs of manufacture, transportation, installation, and maintenance. They do not include mark-up from intermediaries such as distributors or installers and hence are cost estimates rather than end prices charged to the consumer. All costs are expressed in 1978 dollars.

Materials costs were estimated in three ways:

(1) Parts such as pumps and motors were assumed to be obtained from manufacturers of these items for a range of quantities so that cost sensitivity to production volume could be assessed.

(2) For items such as motor controls, sensors and relays that are used in a wide variety of applications, catalog prices were used.

(3) Some items are not currently manufactured. Process steps for fabrication and assembly were defined and labor, investment and raw materials costs estimated for commercial production volumes.

Labor costs for fabrication and assembly were direct labor costs plus burden. For assembly of purchased parts, a burden of 100% was added to direct labor costs. For conventional fabrication and assembly, a burden of 150% was applied. Some cases involved advanced or even presently unavailable fabrication technology; in these instances the burden on direct labor cost was 200%. In all cases, ex-factory costs for labor include a pre-tax profit of 12-18% as would likely be the goal of mature businesses.

In some cases where quotes for production items such as Megatherm were obtained directly from a contractor, the markups used may be inconsistent with the analysis described above in that the initial selling price of these systems appears to include a substantial profit that is consistent with a fledging industry that has made a substantial investment in the development of a product. Thus, it is likely that the baseline costs will drop for some of these systems as production rates increase and competition is introduced from other products. This is especially true for the Megatherm units and for the units employing ceramic bricks for off-peak electric heating. The ceramic brick system cost, however, may not decrease significantly due to the fact that these units have been manufactured for some years in Europe. With Megatherm costs, estimates based on the system components indicate that a cost reduction of from 10% to 25% of the quoted prices may be possible as production quantities are increased.

In addition to estimating the actual cost to manufacture the units, estimates were made of the cost of transportation of the system to the site and installation at the site. In some cases these systems are factory assembled and shipped as complete units, needing only to be charged with heat storage material at the site; while, in other cases the systems are essentially built from scratch at the site using one fabricated element.

Finally for each system application and baseline case, we attempted to estimate the type of maintenance charges that would be associated with the system during a 20-year life. These cost estimates were made by comparing the equipment with similar equipment used in other applications. The system complexity, the number of elements of different types such as pumps and controls, and factors such as the likelihood of corrosion were considered in making these final estimates.

After completing the analysis of each system, the cost data collected were generalized in order to develop cost estimating tools that could be applied to other systems. This was done by plotting the cost of different components versus size or by developing rules of thumb based on different aspects of the systems size and relating them to cost.

These cost estimates considered only first cost. Operating costs (except for maintenance), life cycle costs, etc. were not within the scope of this project. The inclusion of a system as a baseline does not imply that it is economically viable. In addition, costs associated with land use, certification, insurance requirements, etc., were not included but should be evaluated for those systems considered to merit future development efforts.

1.4 Summary of Results

On the following pages, a number of tables are presented that give total estimated costs for thermal energy storage modules compared with a baseline system for different applications. In addition, for the impact on cost due to different mean collector temperatures and to chemical heat pump C.O.P. are presented.

Within each "Application" category, the cost of the baseline system can be compared with the cost of the advanced technologies. It is not meaningful to compare, directly, costs for systems sized for different applications because the systems are different in many operational respects. Thus, since the economic viability of a particular system must really be considered only in terms of the cost of the baseline system with which it is competitive, no attempt has been made to provide an overall ranking. In addition, new developments may reduce the cost of an advanced system to the point that it will be competitive.

In all cases, the cost estimates are based on the assumption that the products are being sold in a mature market structure. The price estimates were made assuming that the product had been fully developed and manufactured in quantity for a period of time. This assumes that normal competitive forces are at work in the market place so that items are priced competitively. Start-up business opportunities are not taking a higher than normal profit to offset initial development costs or to satisfy requirements of venture capitalists for a high rate of return on investment dollars in the early stage of product sales.

- Residential Solar Heating

Cost estimates for storage for residential solar heating are presented in Table 1-1. Three different phase-change systems were costed for this application and compared with the appropriate baseline systems. For hot air systems, a rock bed storage system based on Solaron specifications was used, and for hydronic systems, atmospheric pressure water storage was selected.

The University of Delaware system was the only system with a cost lower than that of the baseline system. However, it has the disadvantage that the output temperature (around 85°F) is significantly below the normal standard of 100°F to 120°F and, therefore, would require a much higher flow rate of air than normal in order to maintain an acceptable discharge rate. This involves higher blower cost, larger air ducts and higher power consumption for blowers.

The Dow system has a delivery rate that is below the rate specified. It would be possible to redesign the system by increasing the surface-to-volume ratio of the cans that are used to contain the heat storage material. However, this would involve a cost penalty for the system.

TABLE 1-1

STORAGE FOR RESIDENTIAL SOLAR HEATING

A) Hot Air

CODE #	CONTRACTOR	TYPE OF SYSTEM	ESTIMATED COST*($)	COST ($)/$10^6$Btu	EXCEPTIONS TO SPECIFICATIONS
B3	Baseline	Solaron Rockbed	1,268	3170	None
11	Dow Chemical	Macroencapsulated PCM $Mg(NO_3)_2 \cdot 6\ H_2O + NH_4\ NO_3$	2,512	6280	Delivery rate 30,000 Btu/hr
13	University of Delaware	Plastic Encapsulated PCM $Na_2SO_4 \cdot 10\ H_2O$	822	2055	Output temperature ≈ 85°F

- Storage Capacity: 400,000 Btu
- Discharge Rate: 50,000 Btu/hr
- Output Temperature 100°F
- Diurnal Cycle

B) Hydronic

CODE #	CONTRACTOR	TYPE OF SYSTEM	ESTIMATED COST*($)	COST ($)/$10^6$Btu	EXCEPTIONS TO SPECIFICATIONS
B2	Baseline	Atmospheric Pressure Water Storage	1,743	4358	None
12	Clemson University	Immiscible fluid $Na_2\ S_2O_3$ & Marcol	2,684	6710	None

* Cost to user including installation.

The Clemson system is more expensive than the baseline hydronic system. This differential would be reduced if an intermediate heat exchanger is not required, but the cost of additional heat transfer fluid plus larger heat exchanger surface areas in the house due to the poorer heat transfer properties of oils would tend to offset this gain.

- Chemical Heat Pump Systems

Table 1-2 compares the cost of the three different chemical heat pump systems costed with a baseline system for each of four HVAC applications.* The baseline system used for this comparison was hot water storage coupled with an Arkla absorption air conditioning system.

For the diurnal applications, both residential and commercial, the systems were sized to provide approximately 50% of the HVAC loads with solar input. In addition to developing cost estimates for the thermal energy storage modules themselves, estimates were made of the solar collector area required for the different applications in three different geographic regions (Boston, Albuquerque, and Fort Worth). For the chemical heat pump systems, two different mean annual collector temperatures were assumed. For the baseline water storage systems, a mean collector temperature of 100°F during the heating season and 200°F during the cooling season was used. As can be seen from the results summarized in Table 1-3, the cost differential between the baseline case and the chemical heat pump system will not be offset by savings in collector area. For the commercial system, similar results can be expected. Other factors, such as maintenance and safety considerations, may suggest that the baseline system would be more attractive for this application.

In one configuration the chemical heat pump could be driven with an auxiliary fuel-fired system when solar inputs were not available. This would reduce the cost of operation when compared with the baseline system and would help to pay back the first cost differential. A more detailed study is required to evaluate these operational considerations.

A similar analysis to estimate the impact of heat pump COP and collector temperature was carried out for the seasonal storage case. The collector areas and storage requirements for these cases are also summarized in Table 1-3. In this application, the chemical heat pump appears to have an advantage both in storage capacity and solar collector areas. This is also evidenced by the cost estimates shown in Table 1-2, which reflect the cost for thermal energy storage modules alone, plus cost estimates with solar collectors added. It should be noted that the Rocket Research

* These are comparisons of first cost only. Because one system is less expensive than another should not be interpreted as meaning that either is cost effective for the application. No analysis of operating benefits was included in this study.

	DIURNAL		SEASONAL			
	COMMERCIAL	RESIDENTIAL	COMMERCIAL		RESIDENTIAL	
	STORAGE MODULE($)	STORAGE MODULE($)	STORAGE MODULE($)	MODULE PLUS COLLECTOR($)	STORAGE MODULE($)	MODULE PLUS COLLECTOR($)
Baseline (water storage plus absorption A.C.)	77,600	12,300	224,600	317,400	36,500	44,500
EIC Corp.	71,900	-	-	-	46,200	53,700
Martin Marietta	69,700	-	-	-	-	-
Rocket Research	94,700	19,800	107,200	173,500	25,000	32,500

TABLE 1-2 SOLAR SPACE HEATING, COOLING, AND WATER HEATING APPLICATIONS USING CHEMICAL HEAT PUMPS

	COLLECTOR AREA (FT²)		
	BASELINE* (WATER STORAGE)	CHEMICAL HEAT PUMP COLLECTOR @ 300°F	COLLECTOR @ 200°F
BOSTON	185	270	185
ALBUQUERQUE	90	102	74
FORT WORTH	125	158	115

* Collector @ 100°F winter and 200°F in summer

A. Collector Area for 50% Solar Residential Diurnal Storage System

	BASELINE (WATER STORAGE)		CHEMICAL HEAT PUMP	
	STORAGE (10^6 Btu)	COLLECTOR Area (Ft²)	STORAGE (10^6 Btu)	COLLECTOR Area (Ft²)
BOSTON				
Residential	28.3	580	9.1	590
Commercial	159.6	5560	36.0	3910
ALBUQUERQUE				
Residential	14.9	260	5.6	200
Commercial	312.3	3030	65.5	2280
FORT WORTH				
Residential	15.4	370	9.0	330
Commercial	368.3	5330	98.8	3770
AVERAGE VALUE				
Residential	19.5	400	8.0	380
Commercial	280.1	4640	65.0	3320

B. Collector Area for 100% Solar Seasonal Storage System

TABLE 1-3 SOLAR COLLECTOR AREA ESTIMATES FOR VARIOUS SYSTEM CONFIGURATIONS configuration that was actually costed utilized low cost storage tanks for the sulfuric acid. If the tanks are found to be insufficient due to corrosion constraints, the cost of the system could be increased significantly. However, a substantial margin still exists between the cost of the baseline system and the chemical heat pump system.

In order to estimate the collector area and storage size, the performance of the systems was modelled. For each system the configuration which met the seasonal loads with the minimum collector area was selected. Rocket Research* indicates that there is a minimum cost configuration which uses more area and less storage. Our model using monthly average weather data shows a minimum cost with zero storage. A more detailed analysis using hourly weather data is needed to resolve the difference. We estimate that the reduction in cost will be less than 20% of the estimates given. A similar reduction should result for both the baseline and the chemical heat pump system.

- Residential Solar Cooling with Absorption Air Conditioner

Table 1-4 compares the cost of the Monsanto system and a baseline system using pressurized hot water for residential solar cooling coupled with an absorption air conditioner. The cost projected for the Monsanto system is below that of the baseline system shown. However, the cost per million Btu's of both systems are much higher than the $4000 to $6000 guidelines typically used, especially when it is considered that the storage capacity is not all converted to useful air conditioning due to the fact that that the COP for typical absorption air conditioners is in the range of 0.6 to 0.7.

- Residential Off-Peak Electric Space Heating

Table 1-5 compares a residential-sized unit utilizing all off-peak electric energy for space heating. The baseline in this case is the TPI ceramic brick unit, which is presently available commercially in the United States in a size somewhat larger than the size shown here. TPI intends to make a unit of the specified capacity available in the near future and the pricing is based on their estimates for a unit of this size.

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* E. C. Clark et al., Sulfuric Acid and Water Chemical Heat Pump, Chemical Energy Storage Program, Contract 18-495 B, Sandia Corporation, 1978.

TABLE 1-4

STORAGE FOR RESIDENTIAL SOLAR COOLING WITH ABSORPTION AIR CONDITIONERS

CODE#	CONTRACTOR	TYPE OF SYSTEM	ESTIMATED* COST($)	COST($)/$10^6$Btu	EXCEPTIONS TO SPECIFICATIONS
B4	Baseline	Pressurized Hot Water (Megatherm)	5,940	23760	None
14	Monsanto	Phase Change Cross-Linked Polyethylene	3,630	14520	None

- Thermal Storage Capacity: 250,000 Btu (Hot)
- Discharge Rate: 35,000 Btu/hr
- Output Temperature: 200°F
- Diurnal Cycle

*Cost to user including installation.

TABLE 1-5

STORAGE FOR RESIDENTIAL OFF-PEAK ELECTRIC SPACE HEATING

COST#	CONTRACTOR	TYPE OF SYSTEM	ESTIMATED COST* ($)	COST($)/$10^6$Btu	EXCEPTIONS TO SPECIFICATIONS
B7	Baseline	Heated Ceramic Bricks (TPI)	1,090	2725	Delivers @ 140°F Includes blower
10	Dow Chemical	Phase Change Macroencapsulated $Mg(NO_3)_2 \cdot 6 H_2O$	1,583	3,958	Delivery rate 30,000 Btu/hr
13	University of Delaware	Plastic Encapsulated Phase Change Material $Na_2 SO_4 \cdot 10 H_2O$	822	2050	Output temperature ≈ 85°F

- Storage Capacity: 400,000 Btu
- Discharge Rate: 50,000 Btu/hr
- Output Temperature: 100°F
- Diurnal Cycle

*Cost to user including installation.

The Dow system costed had a price higher than the baseline system and, in addition, will deliver at a rate less than that specified. As noted above, to increase this delivery rate would result in a higher cost system. With the Dow system, there do not seem to be opportunities for significant cost reductions unless other containers can be found. The University of Delaware system has a competitive first cost, but this will be offset partially by the larger air ducts and air handling equipment required due to the lower supply temperature.

- Residential Off-Peak Electric Cooling

Table 1-6 shows estimated costs for coolness storage using off-peak electricity. The baseline for this application is an ice system patterned after an A. O. Smith unit. It consists of a tank containing a long coil on which ice is formed during charging of the system. The cost estimate for the University of Delaware system is lower than the baseline system. The eutectic material used melts in the temperature range between 50°F and 55°F, and will deliver air at about 58°F during most of a cycle. The system at that temperature does not provide for dehumidification of the air. However, University of Delaware personnel indicate that the dehumidification that occurs at night during charging provides adequate daytime humidity levels.

The Franklin Institute system, although it is somewhat more expensive than the baseline system, does provide an operating advantage in that the phase change occurs at 42°F. This means that the temperature of the fluid introduced into the cooling coil in an air duct will be between 45°F and 50°F. This is a value that matches current HVAC practice. Because the system is charged at a temperature higher than the baseline system, the operating efficiency of the system is higher. This translates into two cost differences.

First, a system charging an ice unit must use a larger compressor with a higher first cost. Offsetting this hardware cost differential partially is the fact that the Franklin Institute system will require a larger heat exchanger in the air duct coil because the temperature differential between the fluid and the air being cooled is smaller than with the ice system. However, a net difference of $100 to $200 in favor of the Franklin Institute system will still result. Thus, the total installed cost of the two systems will be reasonably close. In addition, the Franklin Institute system may be expected to yield a cost savings on the order of $50 per year for a typical installation based on an analysis of the compressor requirements and utilizing the ORNL* annual average energy consumption for air conditioning of 4,400 kilowatt hours per year and an electricity cost of $.04 per kilowatt hour. Thus the Franklin Institute approach using immiscible fluids appears to offer advantages over the baseline case.

* Eric Hirst, Oak Ridge National Laboratory, personal communication, 1978.

TABLE 1-6

STORAGE FOR RESIDENTIAL COOLING USING OFF-PEAK ELECTRICITY

CODE#	CONTRACTOR	TYPE OF SYSTEM	ESTIMATED COST* ($)	COST($)/$10^6$ Btu	EXCEPTIONS TO SPECIFICATIONS
B8	Baseline	Ice	1,205	6025	Temperature to air duct: 32°F
8	University of Delaware	Phase Change $Na_2SO_4 \cdot 10\ H_2O$ (Plus Choride Salts)	642	3210	Delivered air @ 60°F minimum
J	Franklin Institute	Immiscible fluids Trimethylamine - Dowtherm J	1,487	7435	None

- Storage Capacity: 200,000 Btu
- Discharge Rate: 35,000 Btu/hr
- Output Temperature: 60°F maximum
- Diurnal Cycle

*Cost to user including installation.

- Passive Residential Space Heating

Two passive storage systems* are compared in Table 1-7. These systems both employ building materials impregnated with a phase change material to increase their thermal storage capacity. The phase change materials typically melt at room temperature to provide a substantial amount of energy storage capability in the comfort range. In this case, the cost per million Btu's was obtained by offsetting the cost of the block with storage material by the cost of the block without storage material.

The Suntek system has a significantly lower cost per Btu's than does the Brookhaven system. However, the useful storage capacity of the Suntek block may be less than the indicated energy storage capacity because of limitations on the rate at which energy can be removed from the block. We estimate that a reasonable value for energy transfer from the block (based on natural convection and a radiation loss to the rest of the room with a temperature difference of 10°F) is approximately 10 Btu's per hour assuming discharge from one face only. This would mean that a block would take a week to give up its total heat capacity. If the storage capacity of the Brookhaven blocks more closely matches the useful capacity of a block, the cost of this type of storage system per million Btu's is higher than the normal $1000 - $2000 target for hot thermal storage devices. The major cost in these systems is the cost of containing the heat storage material in the block. The more reasonable approach to creating a building block with storage would appear to be to use a smaller amount of material, perhaps 4 to 6 pound of phase change material incorporated directly in the block without any form of encapsulation.

- Aquifer Storage for Space Cooling

Table 1-8 summarizes three different cases using aquifer storage for seasonal cooling applications.** The cost per million Btu's for these systems is a fraction of the cost for the system considered before. The differences between systems #18 and #19 are primarily due to the fact that the Desert Reclamation Industry system utilized deep wells with a larger diameter than the Texas A&M installation. This depends on the characteristics of the aquifer being utilized for storage.

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* Since the completion of the first phase of this program, the Suntek approach as costed has encountered technical difficulities and the Brookhaven program has concluded without identifying promising micro-encapsulated systems. These results are included to provide reference points for future work.

** These costs are dependent on a number of factors and are included to indicate the apparent promise of this type of storage. However, to adequately assess the real cost, a number of socio-economic and environmental questions beyond the scope of this project need to be addressed. Such studies are currently in progress under DOE sponsorship.

TABLE 1-7

PASSIVE STORAGE FOR RESIDENTIAL SPACE HEATING

CODE#	CONTRACTOR	TYPE OF SYSTEM	ESTIMATED COST*($) PER BLOCK	COST($)/$10^6$Btu**	COMMENTS
B1	Baseline	Concrete Block	1.72	N/A	60 Btu/block with 10°F cycle
15	Suntek	Phase Change $CaCl_2 \cdot 6\ H_2O$ impregnated blocks	4.53	2,020	1450 Btu/block, no insulation
16	Brookhaven	Phase Change Microencapsulated $CaCl_2 \cdot 6\ H_2O$	7.05	15,680	400 Btu/block, no insulation

* Cost to user including installation.

** Offset by baseline (See Figure 5-1).

TABLE 1-8

STORAGE USING AQUIFERS FOR COOLING

CODE#	CONTRACTOR	SYSTEM SIZE (Btu)	ESTIMATED COST*($)	COST($)/$10^6$Btu
17	Desert Reclamation Industries	$200x10^9$	4,258,503	21
18	Texas A&M	$4x10^9$	126,956	32
19	Desert Reclamation Industries	$4x10^9$	233,260	58

*Cost to user including installation.

- Summary Results

Table 1-9 summarizes the results for the systems costed. In this table are shown not only the totals for each system, but also a breakdown by major system elements so that each system element can be compared directly with the others. The number in the upper left-hand corner of each block indicates the percent of system installed cost represented by each element. Also shown are estimates of the maintenance cost required for the different systems. These are based on an analysis of the different system elements and a comparison of the maintenance typically required by similar devices in other applications.

The chemical heat pump systems can be charged with a fuel-fired unit leading to a lower operating cost for systems which were less than 100% solar. These savings were not considered in the project.

1.5 Report Organization

The following chapters and two appendices describe in more detail the results discussed in general here.

Chapter 2 discusses the derivation of the classification scheme used to define the range of TES technologies and applications, illustrates the specification of typical operating characteristics that enable a comparison of competing technologies, and discusses the rationale for the selection of reference applications for detailed analysis.

In Chapter 3, the general costing methodology is explained. Chapter 4 describes the TES module that provided the analytical framework for cost comparisons and summarizes system characteristics, operational parameters and costs of each application of the advanced TES concepts. In Chapter 5, similar information is given for the baseline systems.

Chapter 6 analyzes the effect of input storage temperature requirements on solar collector hardware costs and the input temperature requirements of off-peak electric storage systems on compressor operating costs.

In Chapter 7, the effects of chemical heat pump COP and collector temperature on storage size and collector area are considered.

Following Chapter 7 are two appendices containing back-up data on costs of system elements (Appendix I) and generalized cost data for use in estimating costs of other TES systems (Appendix II).

TYPE		CHEMICAL HEAT PUMPS						
CONTRACTOR		1. EIC	2. EIC	3. MM	4. RRC	5. RRC	6. RRC	7. RRC
INPUT		Solar						
CYCLE		Diurnal	Seasonal	Diurnal	Seasonal		Diurnal	
SIZE		Large	Small	Large		Small	Large	Small
OUTPUT		Space Heating, Cooling, and Water Heating						
STORAGE MEDIUM	A	4.0 / 2840	6.1 / 2840	9.6 / 6700	4.0 / 4277	2.1 / 526	0.6 / 526	0.1 / 26
CONTAINER	B	27.1 / 19454	42.1 / 19464	29.4 / 20490	20.0 / 21497	18.4 / 4598	22.5 / 21320	10.1 / 2008
INSULATION	C	0.4 / 256	4.5 / 2059	4.6 / 3215	.05 / 50	0.1 / 36	0.2 / 232	0.2 / 47
HEAT EXCHANGER	D	37.7 / 27098	20.8 / 9620	17.2 / 12000	43.7 / 46820	17.0 / 4249	46.0 / 43554	18.4 / 3655
HEAT TRANSFER: FLUID	E	0.4 / 256	0.6 / 256	1.3 / 940	0.2 / 250	0.1 / 34	0.3 / 250	0.2 / 34
HEAT TRANSFER: PIPING	F	4.4 / 3137	2.2 / 1030	6.9 / 4802	4.7 / 5040	4.7 / 1165	4.8 / 4540	5.9 / 1165
HEAT TRANSFER: BLOWERS & MOTORS	G	9.7 / 6977	3.8 / 1765	12.3 / 8550	5.3 / 5642	4.9 / 1224	6.0 / 5642	6.2 / 1224
HEAT TRANSFER: PUMPS MOTORS	H	1.1 / 809	1.2 / 537	1.9 / 1297	5.2 / 5520	10.9 / 2715	5.8 / 5520	13.7 / 2715
CONTROLS	I	5.1 / 3686	4.8 / 2220	6 / 4167	6.0 / 6421	20.4 / 5098	6.8 / 6421	25.7 / 5098
INSTALLATION	J	10.2 / 7345	13.8 / 6391	10.8 / 7559	10.9 / 11661	21.5 / 5369	7.1 / 6685	19.5 / 3859
TOTAL		71868	46182	69720	107178	25014	94690	19831
MAINTENANCE		4501	3657	6000	7025	1431	6717	1090

TABLE 1-9 DETAILED SUMMARY OF COST ESTIMATES FOR ADVANCED TES TECHNOLOGIES

TYPE		PHASE CHANGE MATERIALS									AQUIFER		
CONTRACTOR		8. U.of D.	9. F.I.	10. DOW	11. DOW	12. CU.	13. U.of D.	14. M.R.	15. SUN.	16. B.N.L.	17. D.R.I.	18. Texas A&M	19. D.R.I.
INPUT		Electrical		Solar							Environmental		
CYCLE		Diurnal									Seasonal		
SIZE		Small									Community	Large	
OUTPUT		Cooling		Heating				Cooling	Heating		Cooling		
STORAGE MEDIUM	A	9.3/60	8.6/128	33.1/524	28.7/720	19.9/533	9.9/81	28.6/1039	22.8/621	70.6/4981	-	-	-
CONTAINER	B	37.7/242	16.5/246	43.1/683	52.0/1307	13.5/363	38.8/319	62.3/2261	-	-	-	-	-
INSULATION	C	2.3/15	.7/11	2.5/40	2.0/50	0.5/14	2.7/22	1.0/35	54.2/1472	-	-	-	-
HEAT EXCHANGER	D	-	6.7/100	-	-	31.3/840	-	-	-	-	8.2/350000	-	10.7/25000
HEAT TRANSFER: FLUID	E	-	66/98	-	-	1.6/44	-	-	-	-	-	-	-
HEAT TRANSFER: PIPING	F	-	.4/6	-	-	-/2	-	.1/6	-	-	2.6/112360	17.6/22363	3.3/7665
HEAT TRANSFER: BLOWERS & MOTORS	G	-	-	-	-	-	-	-	-	-	-	-	-
HEAT TRANSFER: PUMPS MOTORS	H	-	26/386	-	-	14.4/386	-	-	-	-	8.4/359600	21.4/27163	5.4/12630
CONTROLS	I	11/70	12.8/190	4.4/70	2.8/70	6.7/180	8.5/7	1.0/35	-	-	6.6/280200	8.9/11291	3.2/7440
INSTALLATION COST	J	39.7/255	21.7/322	16.8/266	14.5/265	12.0/322	40.1/330	7.0/254	23/625	29.4/2074	74.2/3156343	52.1/66139	77.4/180475
TOTAL		642	1487	1583	2512	2684	822	3630	2718	7055	4258503	126956	233260
MAINTENANCE		33.30	109	54	77	354	43	176	60	0	75000	4082	3265

TABLE 1-9 DETAILED SUMMARY OF COST ESTIMATES FOR ADVANCED TES TECHNOLOGIES (Continued)

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CHAPTER 2

DEFINITION OF REFERENCE OPERATING CHARACTERISTICS

2.1 Introduction

In order to compare the costs of different systems it is first necessary to size those systems to meet the operating characteristics of specific applications. Only then can a direct comparison of storage capacities be made on a meaningful basis. The thermal energy storage module must include all features necessary to make it perform as required. Thus, for example, it is not meaningful to compare the cost of the storage media on a $/million Btu capacity basis because of the total thermal energy storage cost. This program began with the development of a classification matrix for different TES applications and the specification of typical operating requirements for the more important uses of thermal energy storage within each class. The major program emphasis was on residential and commercial applications of TES where significant energy can be saved in the near term. Other programs are analyzing costs of TES when used for power generation and industrial energy conservation and, therefore, these applications were considered to be outside the scope of this program.

The remainder of this chapter describes the classification matrix, the typical operating characteristics required to determine system configurations for costing on a common basis, and the rationale for concentrating on the applications selected.

2.2 Derivation of Classification Matrix

In order to develop a classification matrix, we first conducted a literature survey, collecting many references in the area of thermal energy storage, and, in addition, reviewed the presentations made by contractors at the first annual meeting of TES contractors in Cleveland in 1976. Based on this survey, we identified six general areas of work in the development of TES applications. (These are summarized in Figure 2-1.) The categories are:

- Theory: This refers to those efforts that are involved with the theoretical analysis of the various aspects of using thermal storage. These studies include basic heat transfer calculations, work on defining the pertinent thermo-physical properties of heat storage materials, development of standards to be applied to testing of thermal storage devices, and general planning studies to identify and analyze specific applications for thermal storage.

- Solar: Thermal storage is used to make it feasible to utilize the "free" energy provided by the sun. Since the sun shines only periodically, it is desirable to provide a means for storing its energy for use during cloudy periods or at night.

- Electric Power Generation: This relates to the use of storage to assist the utilities in improving their load factors by displacing peak demands to off-peak time. This can be done either by employing thermal storage at utility sites to generate electricity or to store electric power in the form of heat on the customers side of the meter. This may or may not save energy, but it will make the operation of the utilities more cost effective.

- Cyclic Losses: This refers to the use of storage to reduce the losses which occur when devices start and stop. Typically these losses occur because of the fact that it is necessary for a device to "get up to speed" before it reaches peak efficiency, or because losses occur at the end of a cycle due to the wasting of energy that is put into the system to bring it to its normal operating conditions. Some of these losses can be avoided by using storage so that energy can be added to the system using a smaller capacity device and longer on cycles and extracted on an intermittent basis as required.

- Batch Losses: This refers to the use of storage to make it possible to recover waste heat. In an industrial application, this may occur when a furnace is heated up to dry or cure a material being processed and then cooled down to extract the material. The heat normally lost during the cool down period can be stored and recycled to save energy. In a similar application, heat dumped by a generating process can be recovered and stored so that it will be available as required for other applications such as space heating or water heating of residences.

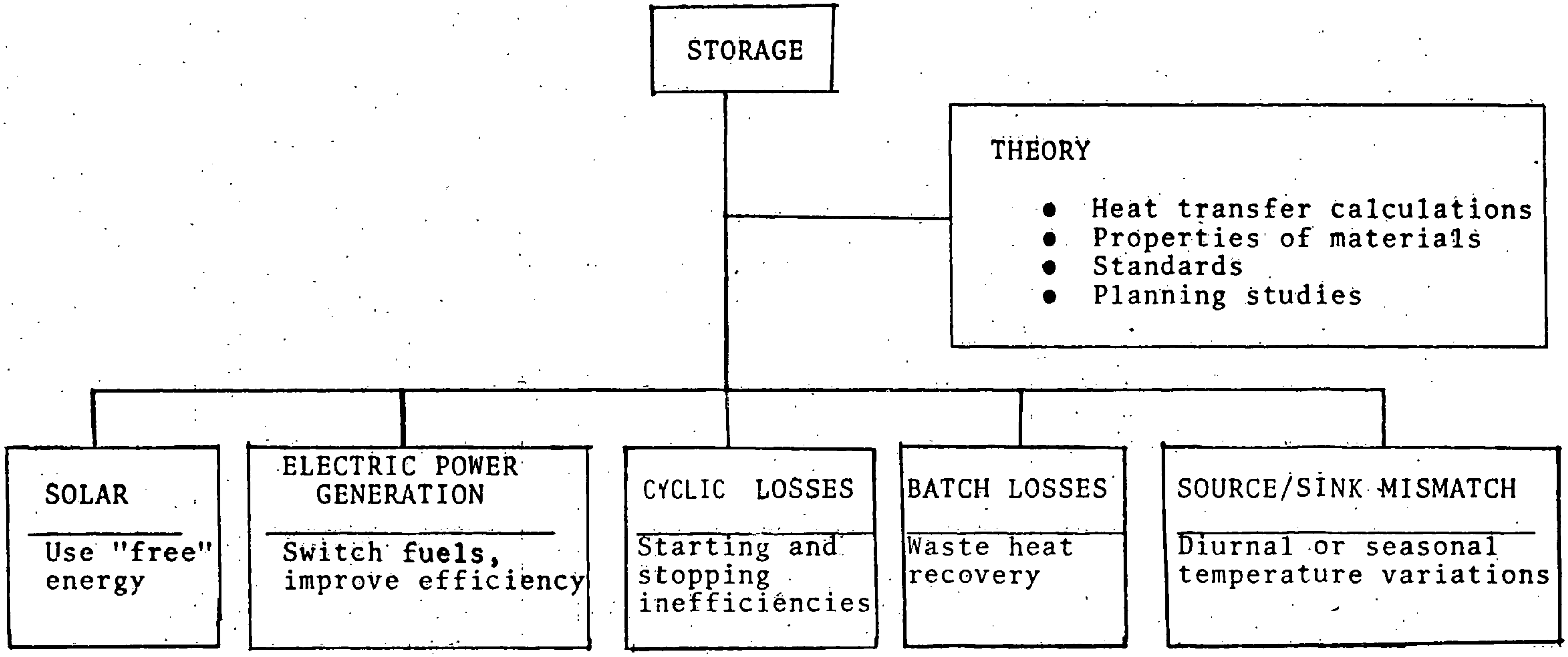


FIGURE 2-1 STORAGE USES

- Source/Sink Mismatch: This covers situations in which storage is used to improve the efficiency of processes which are dependent on ambient temperatures. For example, an air conditioner will run more efficiently when its condensor temperature is lower. Therefore, by running the air conditioner at night and charging a cool storage container, a higher operating efficiency can be obtained. In another example, water can be cooled in the wintertime and stored to serve as a source of space cooling in the summertime.

Figure 2-2 presents a function matrix which provides a basis for categorizing the various thermal energy storage technologies based on the uses for storage as defined in Figure 2-1. On one axis of this matrix are the five categories. The other axis contains specific end uses employing storage. The category "utility" refers to the generation of electricity. "Space heating," "water heating" and "space cooling" are the primary users of energy in the residential and commercial sector. As shown in Table 2-1, 35% of the total energy use in 1970 was consumed by the residential and commercial sector. 22% of the total energy was used for space heating, water heating and space cooling. Transportation is another major energy user. 15% of total energy use in 1970 went to propelling cars. Finally, various commercial processes consumed roughly 40% of our national energy. These are broken down in Table 2-1 into six major categories, which accounted for 19% of the total. Many of these commercial processes are continuous rather than batch type and as such do not lend themselves to the use of energy storage. However, because of the large amount of energy that may be used in a single operation, storage targets do exist which can result in saving substantial amounts of energy.

The breakdown of functions shown in Figure 2-2 encompasses the TES programs currently underway. For illustration a number of these are shown in the proper categories. In the future additional uses for storage may be identified and the end use axis can be extended. The general breakdown along the horizontal axis should include any type of storage system.

For each category of the function matrix, a variety of different sizes of applications exists. For example, solar space heating may be used in systems ranging from the small single family dwelling to a large community system. The economics of the appropriate choice of a thermal storage technology for these ranges of applications will vary. In addition to size, the length of time the energy is stored also will affect the choice of the appropriate technology. Therefore, it is necessary for each category of the matrix to identify a range of applications which will include the different TES technologies. The definition of these performance characteristics is part of Task B.

FIGURE 2-2 FUNCTION MATRIX

GENERAL ENERGY SOURCE

END USE	SOLAR	POWER GENERATION	CYCLIC LOSSES	BATCH LOSSES	SOURCE/SINK TIME MISMATCH
Utility	- hot rocks - latent heat of fusion	- hot rocks - latent heat of fusion			
Space Heating	- hot water - macroencapsulated materials - thermocrete	- electric resistance storage furnace - ACES (weekly)	- fuel fired furnace with storage	- aquifers with industrial waste	- storage heat pump - ACES (Annual)
Water Heating	- hot water	- electric water heater	- flue loss	- drain water recovery	
Space Cooling	- CES - form stable polyethylene	- storage heat pumps - storage air conditioner - ACES (weekly)	- storage heat pumps		- aquifers with cooling ponds - storage heat pump - ACES (Annual)
Transportation		- storage driven Stirling engine	- storage assisted fuel fired Stirling engine		
Commercial Processes	- Desiccant drying			- brick factory	

SECTOR	% of 1970 U.S. Energy Use*	SEGMENT	% of 1970 U.S. Energy Use*
Residential and Commercial	35	Space Heating	14
		Water Heating	4
		A/C	3
		Refrigeration	2
		Subtotal	24
Manufacturing	40	Chemicals	5
		Primary Metals	5
		Petroleum Products	3
		Paper	2
		Stone, Clay Products	2
		Food	2
		Subtotal	19
Transportation	25	Cars	15
TOTAL	100		58

* Based on 1970 Primary Energy Use of Approximately 70 quads.

TABLE 2-1 MAJOR ENERGY STORAGE TARGETS

2.3 Cost Performance Measures

In order to compare the performance of various TES technologies on a common cost basis, it is necessary to incorporate these technologies in systems designed to meet the operating characteristics of specific applications. Due to the economy of scale which usually results in proportionately lower costs for larger systems, measures such as $/kW or $/kWh for different systems cannot be directly compared unless the systems have approximately the same performance characteristics. Therefore, for this analysis, reference applications and output performance requirements have been defined for HVAC applications for thermal energy storage (see Table 2-2). These applications cover the various systems currently under development. By estimating costs for systems incorporating specific TES technologies, it is possible to realistically compare the costs of different types of TES systems since they will be used in the same application and will be sized to provide the same performance. Thus, the values in this table can be the basis for cost/performance measures.

APPLICATION	ENERGY STORAGE (Btu) DIURNAL	SEASONAL	HEAT EXCHANGER DELIVERY RATE (Btu/hr)	TEMPERATURE (°F)	USE
Residential	200,000	4×10^6	35,000	60	Space Cooling
	400,000	8×10^5	50,000	100	Space Heating
	100,000	-	20,000	120	Water Heating
Commercial	8×10^6 to 80×10^6	65×10^6 to 1×10^9	1×10^6 to 10×10^6	60	Space Cooling
	8×10^6 to 80×10^6	65×10^6 to 1×10^9	1×10^6 to 10×10^6	100	Space Heating
	1.5×10^6	-	$.3 \times 10^6$	120	Water Heating
Community	-	1×10^9 to 500×10^9	10×10^6 to 5×10^9	60	Space Cooling
	-	1×10^9 to 500×10^9	10×10^6 to 5×10^9	100	Space Heating

TABLE 2-2 REFERENCE APPLICATIONS

CHAPTER 3

COSTING METHODOLOGY

3.1 Introduction

The following chapter will cover the methods we have employed in determining the costs and prices of each of the energy storage systems covered in this project. To a large extent, the costing of any complex system involves the generation or collection of data on the elements of a system and then the aggregation of this data into a cost. This study posed one additional requirement; the method of data generation or collection needed to be consistent between similar systems and allow comparison between the prices of all the systems.

Due to the dissimilarities between the different energy storage systems, a variety of separate cost/price factors had to be treated. Although most of these factors apply to each of the storage systems, we found a number of instances where one or more of these factors did not apply and frequent instances where the relative importance of these factors varied from system to system. The cost/price factors discussed in this chapter include:

- Purchased Parts
- Factory Costs
- Construction
- Factory vs. Field Labor
- Transportation
- Price vs. Cost
- Quantities
- Maintenance

In discussing each of these factors separately, the reader should recognize that they are highly interactive.

3.2 Purchased Parts

Almost all of the energy storage systems included in this study involve parts purchased from suppliers. An example, representative of many of the systems, is pumps and motors. For the most part, no supplier of storage systems would consider fabricating these components from raw materials simply because there is a well developed industry in this country that can and will provide pumps and motors at costs lower than those at which storage system suppliers can fabricate them. Therefore we have assumed that in each instance where a component of one of the systems is a commodity item, system suppliers will elect to purchase it rather than manufacture it.

In deriving costs for purchased parts, we employed three methods. The first of these involved obtaining quotations from manufacturers of the item in question. For pumps and drives, we specified to the manufacturers; the fluid to be pumped, flow rate, head, plus any other operating characteristics which are critical to the performance of each of the systems treated. In addition, we requested that they provide costs for a range of quantities of these elements. Since different systems are expected to be emplaced at differing annual rates, we wished to obtain cost data which would permit us to gauge the sensitivity of the overall system costs to variations in the costs of its elements and the volume of systems produced in a given period. In addition, since many of the different energy storage systems contained pumps and drives, we were able to collect from suppliers, the cost of a range of pump sizes and types at a variety of different quantity levels. This information is contained in the tables and graphs of the appendix of this report.

A second source of information on the costs of purchased parts are catalogs available from a variety of industrial suppliers. A typical example of the types of commodity items that would have been costed from catalogs includes motor controls, sensor relays and the like. For the most part, the types of items that we elected to cost from catalogs are those that are used in a large variety of different situations and whose cost is relatively standardized from one application to another and one manufacturer to another. Motor starters in general are rated by their size and can be used in any of the storage systems where their size is appropriate. Most manufacturers of these types of commodities are reluctant to provide quotations simply because such information is so readily available from catalogs.

As a third source of cost information, we utilized a technique called simulation. Some elements of some of the systems are not currently manufactured items. As a result, they cannot be costed on a volume basis with traditional methods. In such instances, we presumed that the item in question could be produced in commercial volumes and based our cost analysis on existing products which are now produced in processes similar to those applicable to the item in question. As an example, the Martin Marietta system described in case number 3 consists of a steel tube heat exchanger in a pressure rated vessel. This construction is similar to conventional heat exchangers and to tube bundle type boiler systems. In developing the cost to fabricate this system, we developed the process steps that would be required in fabricating and assembling such a unit and estimated the labor, investment and raw material costs that would be necessary to produce the annual volumes required.

The simulation method of determining costs was used in instances where elements of systems do not now exist commercially and in almost all field installation cases. Wherever it was practical to do so, we utilized supplier quotations and catalog data.

3.3 Construction

In all of the larger energy storage systems covered by this project, as well as many of the smaller systems, some portion of the cost derives from work which must be performed on site. Cases 15 and 16 by Suntek and Brookhaven, for instance, are passive energy storage systems which utilize special filled blocks which are assembled as walls. The manufacturing sequences for the individual blocks are performed in a factory but the installation sequence would replicate the construction of a block wall. To estimate the masonry work required to install these walls, we used labor costs for ground face blocks. We selected ground face blocks because the special filled blocks must be handled in the same manner as the ground face blocks; e.g., damaged blocks cannot be used and care must be taken in handling blocks to insure that physical damage is avoided.

Similarly, in any of the system installations which required plumbing, electrical connections, the installation of special structures, excavation and filling work or the application of field coverings, we utilized labor categories, labor rates and productivity rates common to the domestic construction industry. For the most part, these rates were obtained from the 1978 edition of the Robert Snow Means Company publication, Building Construction Cost Data.* Costs thus derived were, where possible, checked against similar cost in the Construction Publishing Company edition of Building Cost File - Eastern Edition. As an example of this cross check, the labor cost to install these special filled blocks using Means data is $1.40 per square foot and using the Construction Publishing Company data is $1.386 per square foot.

3.4 Factory Costs

There are three components generally included in factory or plant costs. These are material, labor and burden. The material element covers the costs of all components, raw materials and direct supplies that a firm must purchase in order to fabricate or assemble a product. In our analysis, we have listed the material costs for each of the energy storage systems being evaluated.

The labor costs for factory manufactured systems or subsystems have been treated in a different manner. For each system, we have posed a process which could be used to accomplish the fabrication and assembly tasks necessary to manufacture the components of each system. We have based these processes on currently available technologies or on reasonable extrapolations of current technology. After developing each of the processes, we then estimated the manpower that would be required as direct labor to fabricate or assemble the system components at the volume levels anticipated for each of the systems. In most instances, we also assumed that more than one manufacturing facility would be responsible for satisfying national demand. This was particularly the case with systems which would otherwise have high transportation costs.

* Robert Snow Means Company, Inc., Building Construction Cost Data 1978. 36th Edition, Duxbury, Mass., 1978.

We then prepared plant and investment cost analyses for three different types of manufacturing situations. In the first of these, we used those systems which essentially required the factory assembly of purchased parts. In this analysis, we determined that a burden rate on direct labor of 100% yielded ex-factory costs which contained profit margins of from 12 to 18% before taxes. Since this is not an atypical profit goal of mature businesses, we applied this rate to all of the systems requiring only assembly activities. For products requiring conventional fabrication, or fabrication and assembly, we found that a burden rate of 150% of direct labor was required. Lastly, in a small number of cases where the technology of fabrication was advanced or where it was not clear that the needed technology is developed now, we used a burden rate of 200%. This rate corresponds with those used by firms whose products require large continuing engineering or research and development expenditures.

In each situation, we attempted to aim the ex-factory cost so that the plant yielded a profit before taxes in the range of 12 to 18%. We recognize that some of the systems being analyzed may, in their early marketing stages be able to command higher profit percentages due to the high market acceptance that new, novel, efficient energy systems are likely to have in a period of high energy costs. We could not realistically determine what these "extra" profits might be or how long they might remain in force until competition from other systems forced them to more normal levels. We also recognized the possibility that some of the energy storage systems being evaluated might not be economically attractive. In such instances, using "ordinary" plant profit scenarios, these systems would tend to be highlighted as uneconomic. Our analysis assumes that each system is being fabricated and installed in a mature market and that each system must compete with other viable mature alternatives. On this basis, any system whose economics are favorable is likely to enjoy a high market share, a growing market share or above ordinary profits.

Our results do not assume that each of the energy storage systems being evaluated will compete with one another at the same time. Some of the more advanced systems could conceivably take many years to perfect while less sophisticated systems might be constructed later this year. For every system we have assumed that one or more production and marketing organizations will be sufficiently interested in them to put them into production.

3.5 Factory Versus Field Labor

All of the systems covered by this study include both factory and site costs. In general, the smaller systems contain a high proportion of factory cost and the larger systems a high value for field labor. As a general rule, we have tended to maximize the factory content of any of the systems where an option was available. The reasons for this are as follows. Traditionally, the efficiency of site labor is lower than that of factory operations. Various studies that have been performed cite weather, supervision and strong unionization as being key factors in the disparity. In addition, where tasks are repetitive or where the accuracy of operations is an important issue, it is usually more cost effective to invest in equipment which aids an operator in performing repetitive or accurate tasks.

In a plant, management can provide labor saving devices to move, maneuver and operate on the materials and systems being fabricated. They can provide quality control measures at various stages of the operation to insure that the product is being fabricated in a manner that will insure its proper operation. They can simulate operations on portions of the systems and correct defects before the units are shipped. In short, they can manage the products that are shipped from the plant.

In a system where field erection and fabrication are a significant portion of the cost, labor saving devices except for material handling are less in evidence. Most testing is performed at the conclusion of a project with the result that defects, when they are discovered, can be difficult to repair. Usually, there is little opportunity to replace significant portions of a system with the result that field "fixes" must be made.

Although efforts are made to control the quality of field activities, these efforts frequently depend on the experience of the field supervisors. To a large extent, the inspections consist of visual checks of work performed rather than the physical testing that can and is performed in most manufacturing plants.

Nevertheless, there is, for each system, at least a minimum quantity of field labor that is required to install and connect the systems. In our analysis and generation of costs, we have attempted to integrate the maximum quantity of assembly and fabrication in a plant environment so that field problems are held to minimum quantities.

3.6 Transportation

All of the energy storage systems included in this project involve a need to transport materials, components or packaged portions of the systems from one location to another. In the first instance, purchased components such as pumps, motors, control elements, etc., are shipped by the various suppliers to assumed assembly or fabrication plants. To avoid the necessity of creating transportation estimates at this step, we requested all of the quotations with delivery costs included.

Similarly, when an installation contractor either picks up material at his supplier or transports a system from his place of business, a transport cost is involved. In this instance, we have included such costs in the labor elements associated with each installation.

The one area in which we had to prepare a set of separate estimates for transport of each of the systems involves the movement of a system from the fabrication or assembly factory to the dealers or wholesalers premises. In these instances, we estimated the quantity of material to be shipped and based on those estimates and ordinary I.C.C. rate schedules applied the transportation costs as a percentage of the ex-factory cost.

In a small number of the larger systems, such as those being proposed by the Desert Research Institute, we have assumed that the major components of the system will be transported directly from the fabrication plant to the sites. In these instances, the components of concern will undoubtedly be engineered for a specific project so that intermediate parties and storage locations will not be necessary.

3.7 Maintenance

In most mechanical, chemical and electrical systems, or combinations of these, the costs necessary to maintain the components and system as a whole can be stated as an annual percentage of the system's first cost. Typically, these percentages range from a low of 2% for electrical components in the power supply loops to a high of 15% for "disposable" components of certain types of chemical-mechanical components.

As examples, home hot water heating systems, independent of other appliances and locally available from many retail outlets, have a typical life of 5 to 15 years, with the national average being approximately 7½ years. During the span of a water heater's useful life, little if any maintenance is performed on it except for the replacement of defective elements. Under the large majority of circumstances, these defective components are detected during the warrantee period and are repaired at no cost to the user. During its life, a large number of factors affect its utility and ultimately its life. First, the unit is subject to thermal cycling which breaks down the tank lining. Given time, such breakdown will cause penetration of the lining and corrosion of the tank. If not repaired, the tank will ultimately leak. Second, dissolved elements in the supply water will "coat out" on the electrodes and the lining. Most tanks provide for such coating by oversizing the electrodes but even with this provision, time will reduce the efficiency of the heater system. Third, the electrodes themselves, after prolonged periods of thermal cycling and coating buildup will begin to harden and/or develop "hot spots" which in time lead to breakdown both mechanically in the electrode and electrically in the electrode, its connectors and in the insulation.

Similarly, other environmental factors affect the tank insulation, the outer casing, the control section and in the case of gas fired heaters, the piping controls and burner section. The result of these gradually accumulating defects is that when one of these defects reaches a critical stage requiring service, it does not pay to service the unit (in most cases) since other elements of it will fail in the near future. The most prevalent remedy is to replace the unit with a new water heater. This effectively displaces the maintenance costs to one lump figure which is the replacement cost. Using the 7½ years as the average life, the replacement cost stated as an annual cost of maintenance is 13.3%.

An alternate example displaying the other extreme of maintenance cost would be analogous to power equipment and wiring in a home. Typically, maintenance costs tend to stabilize at approximately 1 to 2% annually of the first cost of the system. Typically, the failures which occur in these systems are either the result of a malfunction in a connected unit such as a short circuit in a washer, dryer or other appliance which burns out a fuse or circuit protector or a failure at an extremity of the system such as in a switch or receptacle. Very rarely does the power box connections or the wiring itself fail although such instances are included in the maintenance cost allowances.

To establish realistic maintenance costs for the components of the Advanced TES Systems, we must treat the different components that make up each of these systems and establish appropriate costs for each element. Based on experience in other industries, we estimate these costs as follows:

Component	Service	% of First Cost to Be Assigned for Upkeep
Container - no liquid	Heat Sink - solid material	1%*
Container - treated water	Heat Sink - water based	4%*
Container - untreated	Heat Sink - water based	8%*
Container - liquid chemical non caustic	Heat Sink - chemical based	8%8
Container - liquid chemical caustic	Heat Sink - chemical based	12%*

* These percentages are standard for operating temperatures between 34°F and 200°F. For each additional 50°F extension to either end of this range, add 1% to upkeep.

Insulation - unprotected indoors	Thermal barrier	4%
protected indoors	Thermal barrier	2%
protected outdoors	Thermal barrier	4%
protected in-ground	Thermal barrier	3%

Component		Service	% of First Cost to Be Assigned for Upkeep
Heat Exchangers	- air to air	Entry or exit to sink	5%
Heat Exchangers	- water to air	Entry or exit to sink	8%
Heat Exchangers	- water to water	Entry or exit to sink	6%
Heat Exchangers	- air to chemical	Entry or exit to sink	9%
Heat Exchangers	- water to chemical	Entry or exit to sink	10%
Heat Exchangers	- chemical	Entry or exit to sink	9%
Heat Transfer Fluid	- air (other)	Media	0%
Heat Transfer Fluid	- untreated water	Media	50%
Heat Transfer Fluid	- treated water	Media	25%
Heat Transfer Fluid	- chemical	Media	15%
Piping	- air systems	-	3%
Piping	- untreated water	-	5%
Piping	- treated water	-	2%
Piping	- chemical	-	4 to 10%
Pump/Blower	- air	Prime/Mover	4%
Pump/Blower	- untreated water	Prime/Mover	8%
Pump/Blower	- treated water	Prime/Mover	6%
Pump/Blower	- chemical	Prime/Mover	6 to 15%
Motor		--	1%
Control Elements		--	7%
Resistance Heaters		--	15%
Cabinetry		--	3%

It should be noted that the maintenance percentages described above include the cleaning of the components on a regular basis where required, change out (as in the case of media) on a regular basis and/or the replacement upon failure of elements (as in the case of resistance heaters).

CHAPTER 4

DESCRIPTION OF SYSTEMS

In this chapter, each system is described and the assumptions made in estimating its costs such as method of assembly materials costs, operation characteristics, etc., are described. In Section 4.1, the definition of the "thermal energy storage module" as used in this study is presented. The individual modules are discussed in Section 4.2.

4.1 Definition of TES Module Costed

In order to develop cost estimates of various systems on a common basis, it is necessary to define a thermal energy storage module so that similar input and outputs from a control volume around the module would be suitable for the different advanced technologies being considered. In general, a thermal energy storage system can be divided into three parts as shown in Figure 4-1. The input section consists of those parts of the system which collect the energy to be stored and transfer it to the storage module. The storage module itself consists of all the components required to receive the energy from the input section and to transfer it to the application plus those components required to store the energy over the desired period of time. The control system components such as thermostats, contactors, etc., required for this process would be included as part of the storage module. The application section of the thermal energy storage system includes those portions of the system required to extract the energy from the heat storage system and pass it to the point of final use. When the storage module is defined in this way, all circulation pumps and pipes external to the basic storage system fall either on the input or application side. Heat exchangers required to transfer energy from the input to the storage medium or from the storage medium to the heat transfer system for transmission to the application are considered to be part of the storage module itself.

For heating and cooling applications for most active systems, the storage module can be represented as shown in Figure 4-2. In this case, several different paths are provided for transferring energy from the input to the load either to the TES module around it, or extracting heat or energy from the TES module and transferring it to the load. The external piping at ducts, the devices for circulating the energy from the input to the load, the collectors on the input side, the heat exchangers on the load side, and the control system operating the various pumps, blowers, valves, etc. are common to all storage heating and cooling systems. However, for heat transfer loops which involve liquids for inputting and extracting energy from the TES module, pipes and pumps will be used with liquid pipe input devices such as a liquid solar collector or a Freon-to-liquid heat exchanger for inputting coolness and a liquid air type heat exchanger on the load side. On the other hand, an air based heat transfer system would require blowers, ducts and motorized dampers, air-to-air heat exchange, air type solar collectors or air-to-liquid heat exchangers on the input side. The cost of these systems will be different and some will be better suited for new installation while others will be better suited for retrofit applications. For the purposes of this study, these portions of the systems are considered to be outside of the thermal energy storage module and the differences in cost of the input and load side heat exchange systems will generally be neglected. However, the effect of input temperature requirements on the cost of the solar collector system and input temperature requirements on the hardware and operating cost of a compressor for applications involving coolness storage have been analyzed.

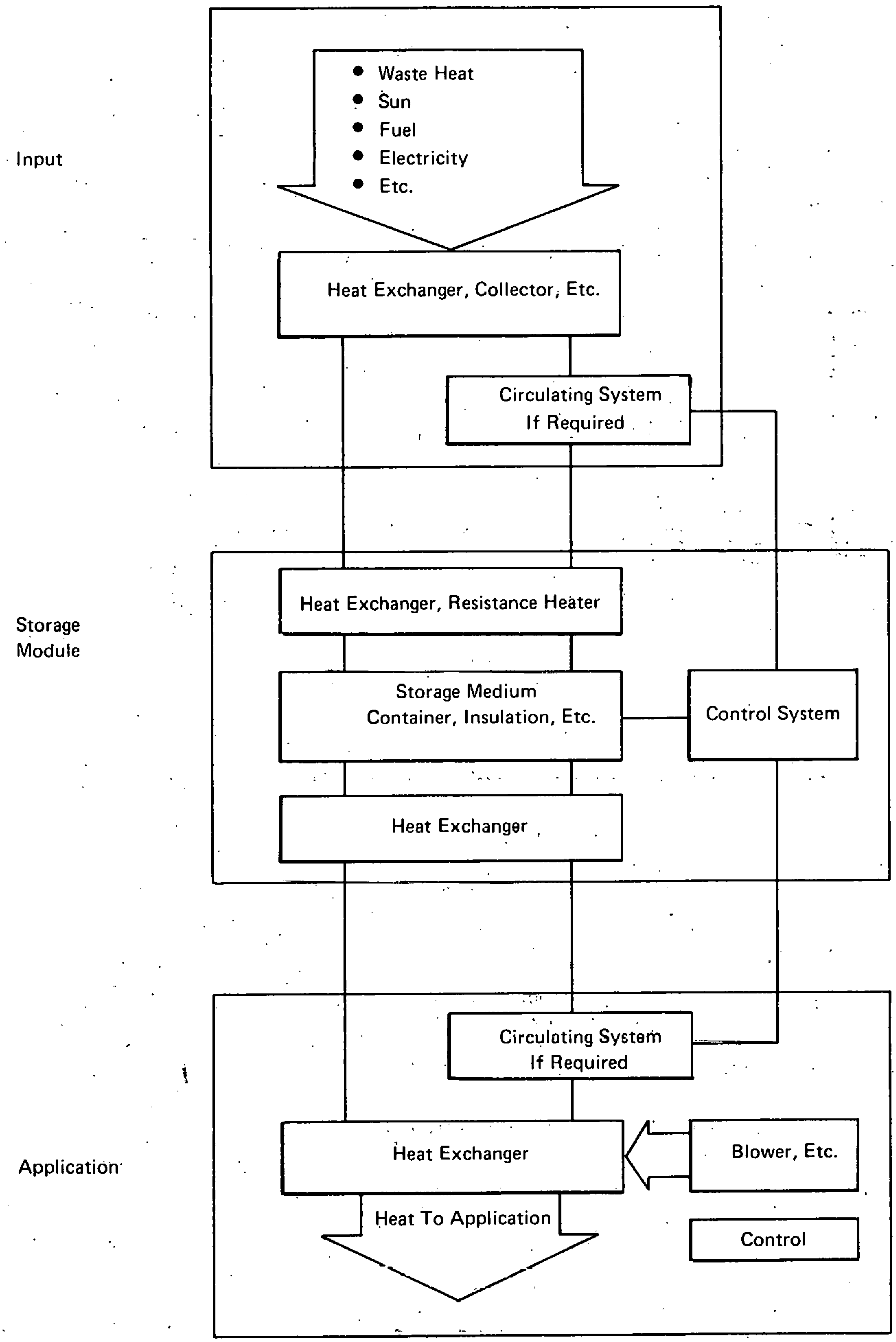
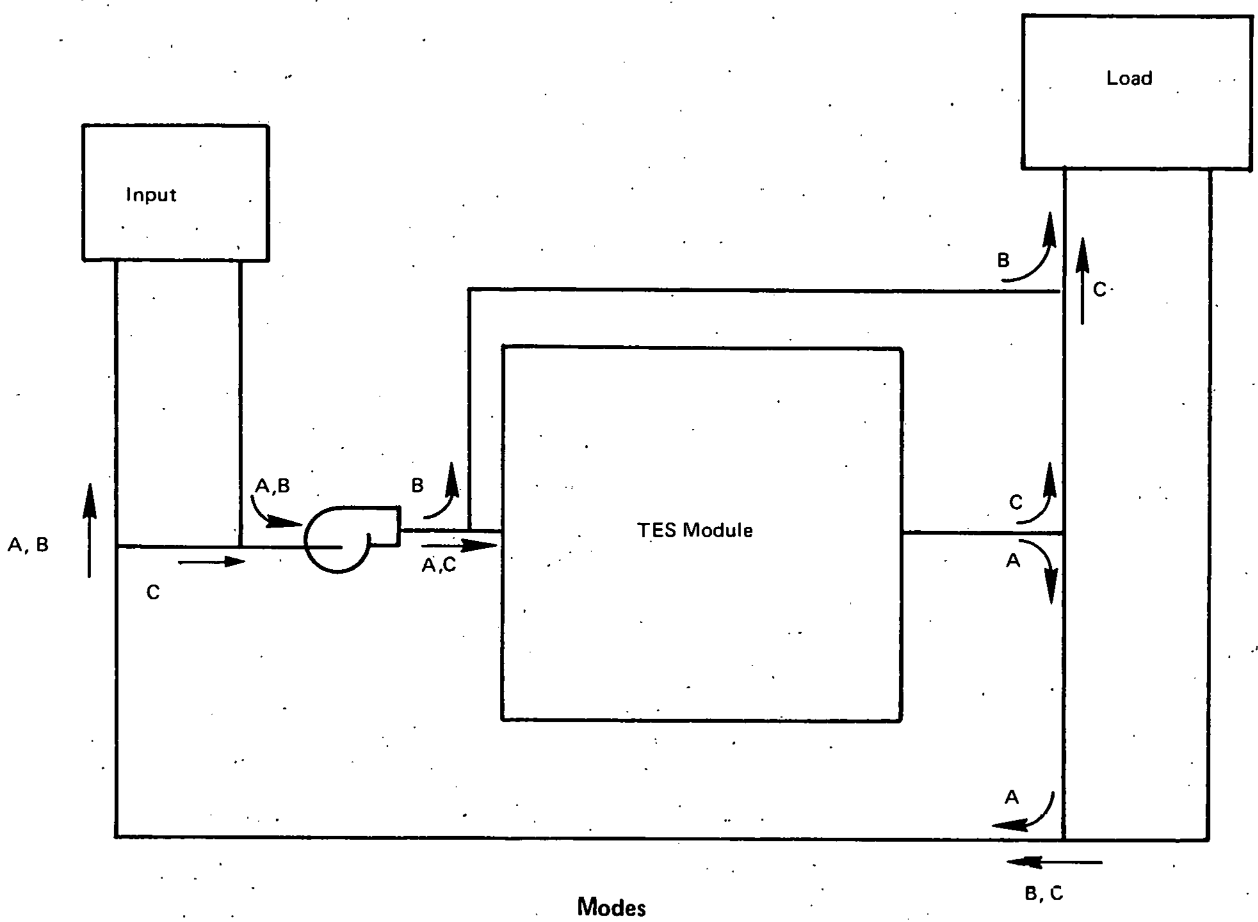


FIGURE 4–1 TES STORAGE SYSTEM



Modes

A. Charging Storage
B. Heat or Coolness from INPUT to LOAD
C. Heat or Coolness from STORAGE to LOAD

Inputs

- Heat From Solar Collector,
- Heat from Resistance Heater (Off-Peak Electric),
- Coolness From Evaporator (Off-Peak Electric).

FIGURE 4–2 DEFINITION OF TES MODULE FOR HVAC APPLICATIONS

Neglecting these differences can be justified because systems requiring similar heat transfer methods will be compared with baseline systems utilizing similar transfer systems. Thus, for example, a heating system which utilizes a hydronic or liquid input and output, will be compared with a baseline system utilizing water as the storage medium, while a thermal energy storage system, using air as the heat transfer medium will be compared with a rock bed storage system which utilizes air as the heat transfer medium. Thus, similar systems can be compared against each other and an appropriate baseline case for each class can be used.

There are basically four types of systems which have been considered for this study, they are:

- chemical heat pumps;
- active phase change;
- aquifer;
- passive phase change.

Each of these systems can be incorporated in a thermal energy storage module, as described above. However, the degree of complication of this system within that module varies considerably, depending on the type of system.

The chemical heat pump systems require a low temperature source-sink for charging and discharging the system. This source-sink must be available at a temperature of approximately 50^{o}F to put heat into the system when it is being discharged and to provide a sink for heat when the system is being charged. This requires a completely separate heat transfer system from that which is used to input energy to the system and to extract energy from the system. It will include heat exchangers, piping and ducting, controls and circulating pumps or blowers. Passive systems, on the other hand, consist of a building material impregnated with a phase change heat storage medium which requires no input or output devices other than those which occur naturally. There are no controls because the system charges or discharges depending on ambient conditions and cannot be controlled. Despite their differences, all of these systems can be incorporated into a system which includes a thermal energy storage module as defined above. Neglecting the heat transfer loops for inputting and extracting energy, units sized for the same application can be costed and costs compared on a roughly equivalent basis.

For the purposes of this study, the low temperature source-sink for chemical heat pumps was assumed to be air at a temperature of 50^{o}F in the winter time and 80^{o}F in the summer time. The choice of temperatures are somewhat arbitrary; however, the 50^{o}F value is marginal in terms of operating characteristics for some systems while others can operate with ambient temperatures much lower than 50^{o}. The 80^{o} value is a reasonable mean for summer type conditions.

Choice of air as the source-sink media, rather than water was made because it is clear that air will always be available for any installation as the source-sink media; whereas, applications where water can be used for this purpose are limited. Since the other systems being costed can all be used in any location, we selected a source sink media which meets the same requirements for the chemical heat pumps systems.

The major impact of the use of air rather than groundwater for the project lies in the costs of the air to liquid heat exchangers and air handling equipment as contrasted to the costs of wells, piping, pumps, and liquid to liquid heat exchangers. Rough estimates indicate that the groundwater hardware would be more expensive.

The use of groundwater has an operational benefit in that it extends the utility of chemical heat pumps to colder climates where the night air is not usable. It also would improve the storage density for systems limited by cooling storage capacity. In our analysis we found that this condition occurred in Forth Worth, but not in Boston or Albuquerque. If groundwater were used with the baseline system, a cooling tower would not be needed and the storage temperature could be reduced saving collector area and storage volume due to the reduced standby losses.

In the following section, each of the systems costed is described in more detail. The baseline systems are described in Chapter 5 in a similar fashion.

4.2 Description of Advanced TES Systems Costed

4.2.1 EIC Corporation (Configuration 1)

- Application

This system (see Figure 4-3) is designed to provide space heating, space cooling, and water heating for a small apartment building. It uses a diurnal storage system and solar input to meet 50% of the annual total building load.

- System Description

The storage module consists of two vacuum tanks containing calcium chloride racks, which also serve as heat exchangers, plus a tank for storing condensed methanol. The pressure in the system will always be less than atmospheric at normal operating temperatures. Two calcium chloride tanks are used to permit switching from one to the other so that the unit can be charged at the same time that it is providing heating or cooling. The heat exchangers containing the calcium cloride are fabricated from conventional, finned tubing used in convection radiator systems. The calcium chloride is packed in the spaces between the fins and held in place with a light-weight metal box. Four passes of heat exchanger tube are used per module. These are manifolded together within the vacuum tank container and a single inlet and outlet provided. The container is a large horizontal tank with a flanged end to permit access to the calcium chloride modules. The storage container for the methanol is a 2,660-gallon ASME vacuum tank mounted horizontally. This tank is 6.5 feet in diameter and 10.7 feet long. A system of ducts and motorized dampers plus solenoid values is provided to permit various modes of operation. The duct work in this system is an add-on to a basic heating system required for charging and discharging this system during these different operational modes. Therefore, it is included as part of TES module. The air to methanol heat exchangers are positioned directly in the air ducts. No secondary heat transfer loops were used in this case. Methanol is not classified as a refrigerant according to the existing standards. If it were determined that a secondary heat transfer loop is required, the addition would have a significant impact on the cost of the system.

- Installation

It was assumed that this unit would be installed indoors. The calcium chloride heat exchanger modules would be shipped to the site and installed in the tanks. An allowance was made for hooking up the plumbing and electricals as necessary at the site. The methanol container would also be installed at the site, but would come as a package, with saddles for support, insulation and pumps and some controls mounted on the unit. Cost estimates for this system are presented in Table 4-1.

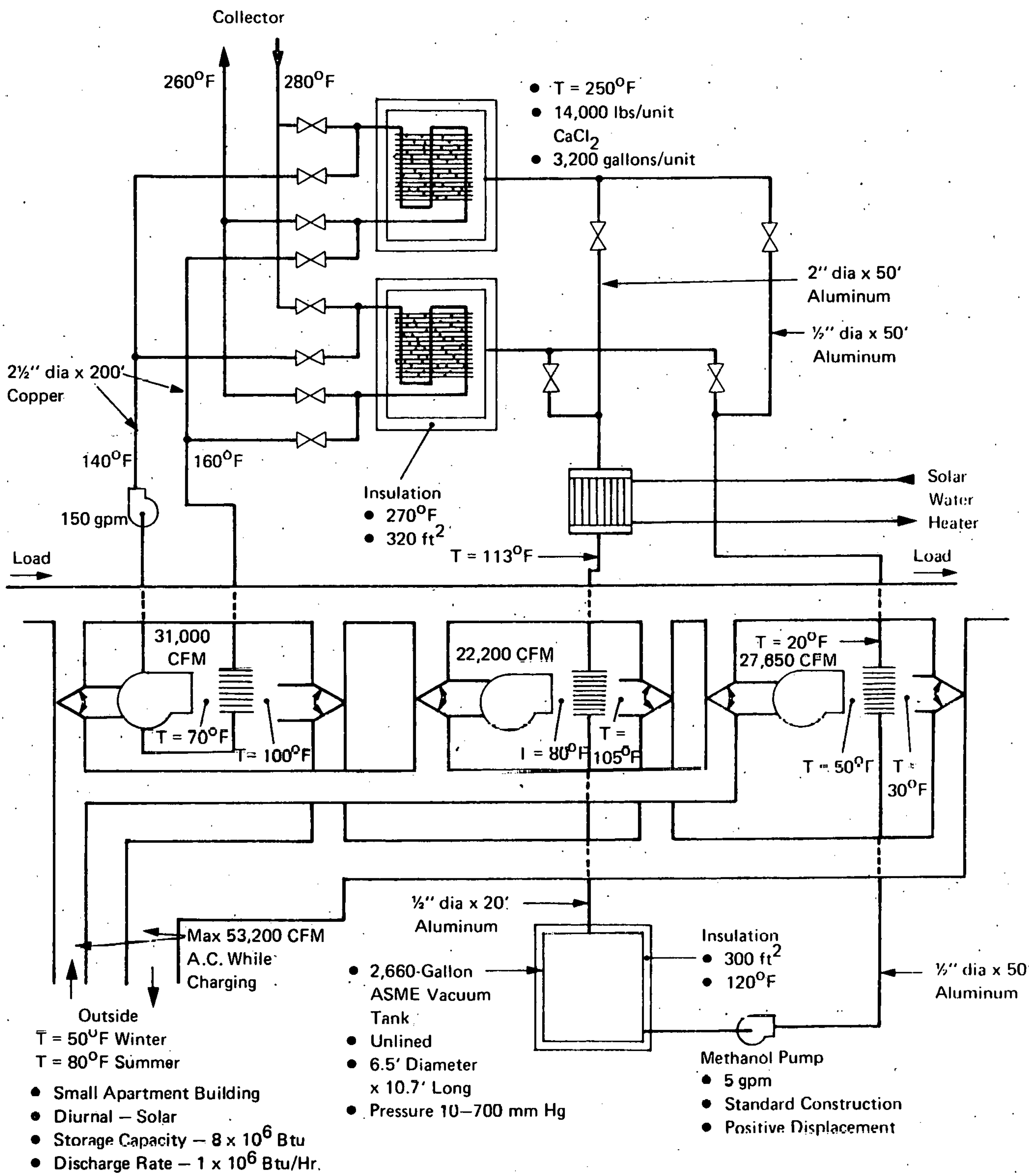


FIGURE 4–3 EIC CORP. (CONFIGURATION #1)

TYPE: CHEMICAL HEAT PUMP

CONTRACTOR: EIC Corporation (Code #1)

INPUT: Solar

CYCLE: Diurnal

STORAGE CAPACITY: 8×10^6 Btu

DISCHARGE RATE: 1×10^6 Btu/hr

			(%)
STORAGE MEDIUM	A	$ 2840	4.0
CONTAINER	B	19464	27.1
INSULATION	C	256	0.4
HEAT EXCHANGERS	D	27098	37.7
FLUID	E	256	0.4
PIPING AND DUCTING	F	3137	4.4
BLOWER & MOTOR	G	6977	9.7
PUMP & MOTOR	H	809	1.1
CONTROLS	I	3686	5.1
INSTALLATION COST	J	7345	10.2
SYSTEM COST		71868	100%
COST OF MAINTENANCE PER YEAR		4501	
NO. OF SYSTEMS PER YEAR		6000	

Table 4-1

COST SUMMARY - EIC CORPORATION (CONFIGURATION 1)

- Operating Characteristics

This system will operate over a range of ambient temperatures without any significant effect on the delivery or output of the system. Because the process involves the condensation of methanol rather than the chemical capturing of methanol by another salt, the lower the ambient temperature the more rapidly the methanol can be condensed. However, lower temperatures limit the storage content. Since methanol will not freeze over the normal operating temperature range this is not a consideration. However, as noted above, should a secondary heat transfer loop be required, the effective storage capacity of the unit as well its cost would change.

4.2.2 EIC Corporation (Configuration 2)

- Application

This configuration (see Figure 4-4) of the EIC Corporation system is applicable to a residence with seasonal storage using solar input. The system is designed to meet 100% of the space heating, space cooling, and water heating loads.

- System Description

This system is quite similar to the system costed as Configuration 1. In this case the storage module is essentially the same, but the heat exchange system has been redesigned to deliver energy at a rate appropriate for a single family dwelling. The tanks were costed for outdoor installation, using insulation covered with a waterproof cementitious coating.

- Installation

With the exception of locating the tanks outdoors, the installation of this system would be the same as Configuration 1. Cost estimates are shown in Table 4-2.

- Operating Conditions

Operating conditions are the same as those for Configuration 1.

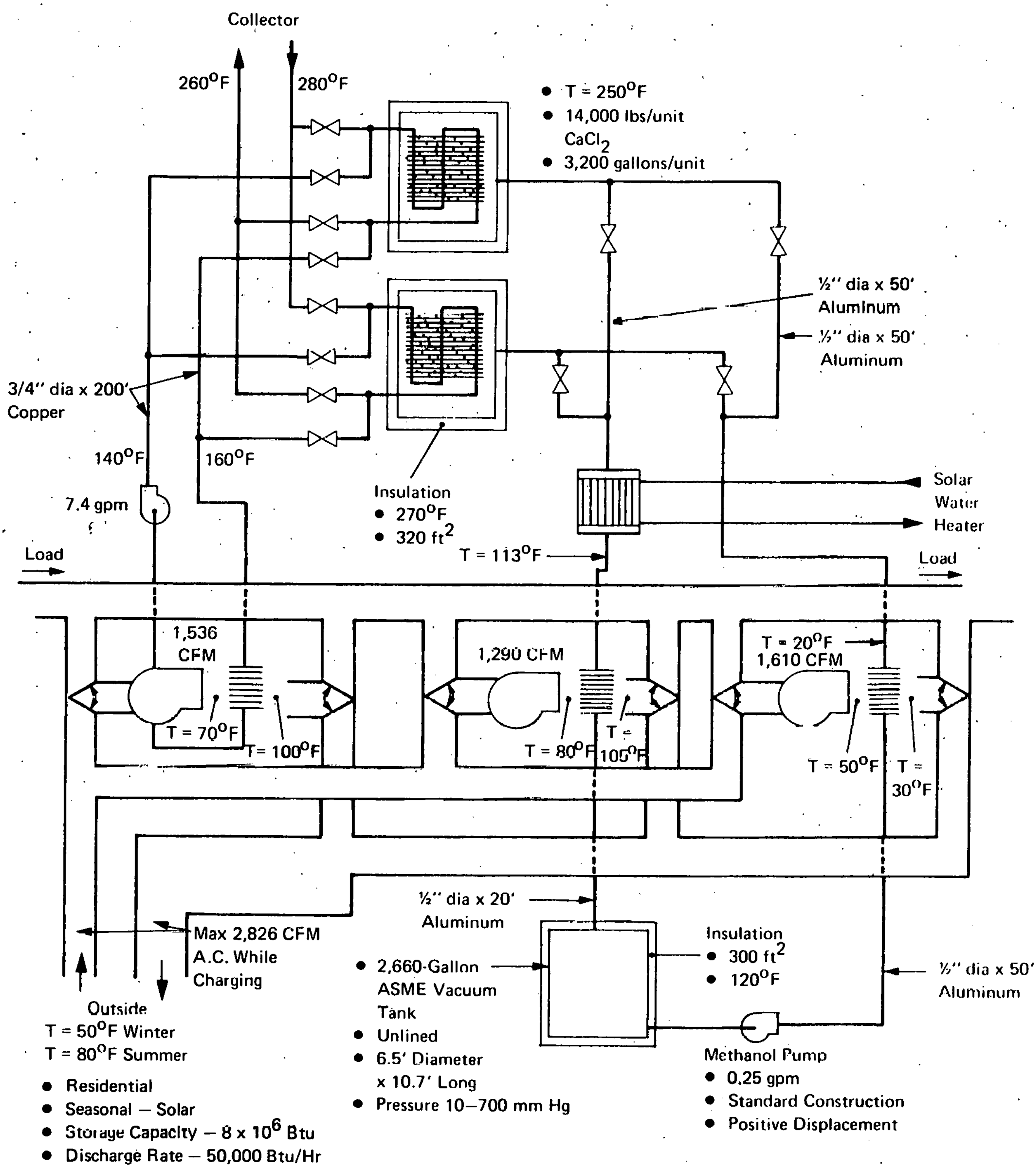


FIGURE 4–4 EIC CORP. (CONFIGURATION #2)

TYPE: CHEMICAL HEAT PUMP

CONTRACTOR: EIC Corporation (Code #2)

INPUT: Solar

CYCLE: Seasonal

STORAGE CAPACITY: 8 X 10^6 Btu

DISCHARGE RATE: 50,000 Btu/hr

			(%)
STORAGE MEDIUM	A	$ 2840	6.1
CONTAINER	B	19464	42.1
INSULATION	C	2059	4.5
HEAT EXCHANGERS	D	9620	20.8
FLUID	E	256	0.6
PIPING AND DUCTING	F	1030	2.2
BLOWER & MOTOR	G	1765	3.8
PUMP & MOTOR	H	537	1.2
CONTROLS	I	2220	4.8
INSTALLATION COST	J	6391	13.8
SYSTEM COST		46182	100%
COST OF MAINTENANCE PER YEAR		3657	
NO. OF SYSTEMS PER YEAR		1000	

Table 4-2

COST SUMMARY - EIC CORPORATION (CONFIGURATION 2)

4.2.3 Martin-Marietta

- Application

The Martin-Marietta system, shown in Figure 4-5, is designed to provide space heating and cooling, and water heating for a small apartment building using diurnal storage and solar input. The system was sized to meet 50% of the yearly loads with solar.

- System Description

This system utilizes two tanks filled with a proprietary liquid ammoniated salt for the high temperature reactors. During charging, the salt in these containers is heated, driving off the ammonia, which is condensed at around 115°F and collected in a steel pressure vessel. The pressure in this case runs significantly above atmospheric. At 250°F, pressure in the high-temperature reactors is 200 PSI. This is beyond the normal rating for propane standard tanks. In addition, the construction of this storage reactor requires the installation of a large tubular heat exchanger. In order to allow for installation and servicing of this heat exchanger, we assumed a flanged connection on one end of the tank. This required a custom tank, and therefore, the costs were based on the pressurized tank curves shown in Appendix II.

The heat transfer system used in this case involves a secondary heat transfer loop to carry heat and coolness from the storage module to the HVAC system. We have assumed that the heat storage module and all portions of the system containing ammonia must be located outside the dwelling as required by existing ASHRAE codes for ammonia-based cooling systems.

The tanks were insulated and covered with a cementitious waterproof coating for outdoor installation.

- Installation

In estimating the cost of installing the system, we assumed that the tanks would be shipped to the site empty and filled with heat storage medium after being installed. An allowance was made for hooking up ducts, heat exchangers, piping and electricals. It was assumed that much of the valving was mounted and prewired at the factory and thus that minimal field work would be required. The installation costs include both factory and field costs. Cost estimates are given in Table 4-3.

- Operating Conditions

The system as shown should provide space heating and cooling at a reasonable temperature and rate for typical HVAC systems. However, in order to avoid excessive pressures and temperatures while charging in the summer time, it may be necessary to provide a cooling tower to keep the condensing temperature low enough to completely charge the system under these conditions.

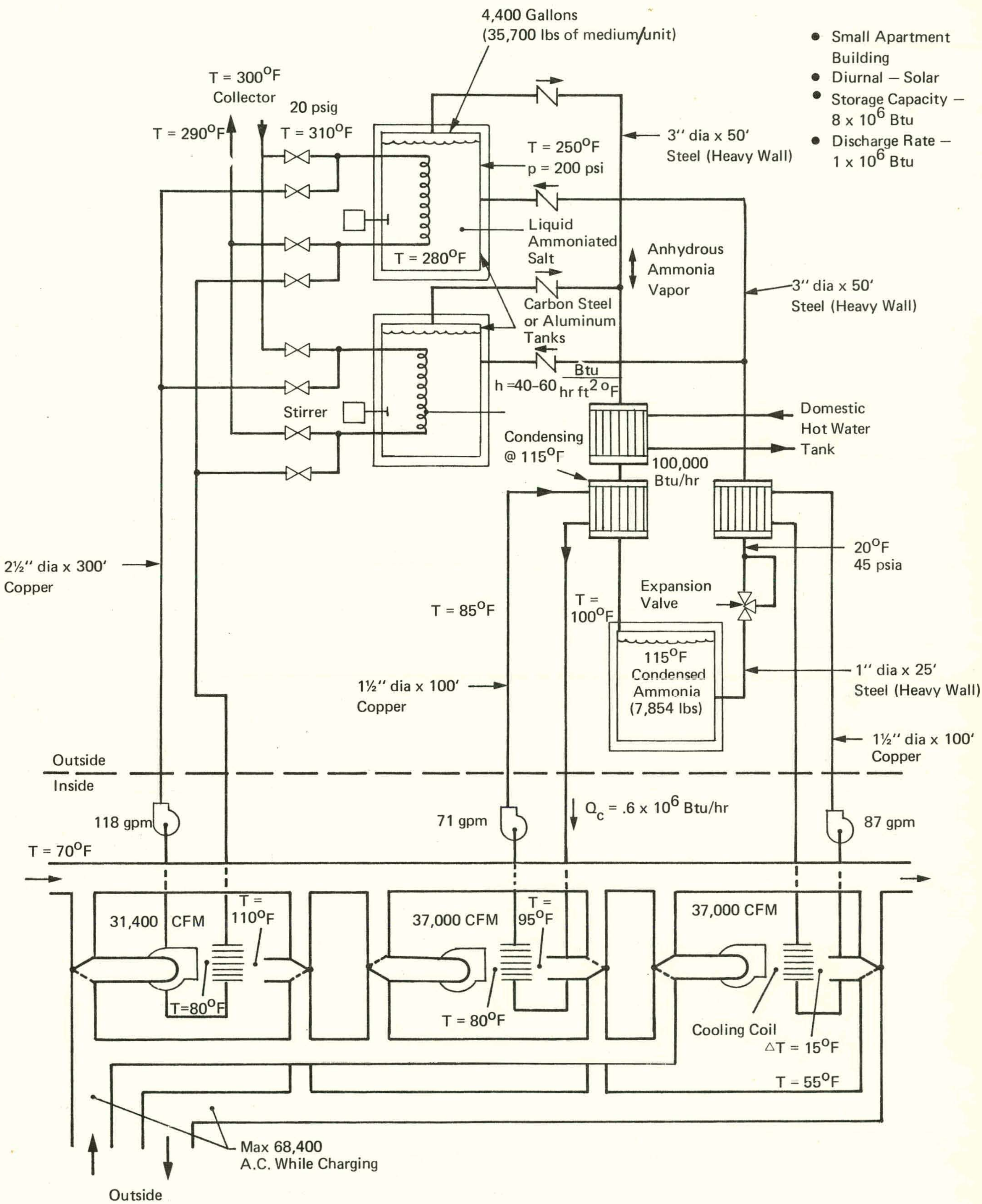


FIGURE 4–5 MARTIN MARIETTA

TYPE:	CHEMICAL HEAT PUMP
CONTRACTOR:	Martin Marietta (Code #3)
INPUT:	Solar
CYCLE:	Diurnal
STORAGE CAPACITY:	8×10^6
DISCHARGE RATE:	1×10^6 Btu/hr

			(%)
STORAGE MEDIUM	A	$ 6700	9.6
CONTAINER	B	20490	29.4
INSULATION	C	3215	4.6
HEAT EXCHANGERS	D	12000	17.2
FLUID	E	940	1.3
PIPING AND DUCTING	F	4802	6.9
BLOWER & MOTOR	G	8550	12.3
PUMP & MOTOR	H	1297	1.9
CONTROLS	I	4167	6
INSTALLATION COST	J	7559	10.8
SYSTEM COST		69720	100%
COST OF MAINTENANCE PER YEAR		3798	
NO. OF SYSTEMS PER YEAR		6000	

Table 4-3

COST SUMMARY - MARTIN MARIETTA

4.2.4 Rocket Research Corporation (Configuration 1)

- Application

In this configuration (shown in Figure 4-6) solar input is used to provide heating, cooling, and water heating to a small apartment building using a seasonal storage system. The system is designed to meet 100% of the HVAC loads.

- System Description

This system uses two large tanks to store concentrated sulfuric acid and water. Both of these tanks are at atmospheric pressure, although the reaction that stores or liberates heat takes place under vacuum conditions. In order to charge or discharge this system, pumps are used to pump fluid back into the tanks against a pressure regulator. This arrangement significantly reduces the cost of the storage system. In the design of the seasonal system, it was assumed that the use of large tanks, which are installed outdoors without insulation, assures that the temperature of the acid in the storage tank will stay below 120° or 130°F. This is accomplished in part by using a heat exchanger to recover some of the heat being returned to the tank during the charging period. Although not required by code, secondary heat exchanger loops are utilized in this design in order to make it possible to heat the building either directly from the solar collector or from discharging storage. This does remove the possibly undesirable requirement for circulating concentrated sulfuric acid through the heating ducts. Cost estimates are given in Table 4-4.

- Installation

As with other large-scale installations, most assembly of this system is done on-site. It was assumed that large tanks and other components were shipped to the site and mounted on appropriate foundations. The installation was completed by hooking-up the electricals, plumbing, and ducting as required and charging the system with acid and water shipped to the site in trucks.

- Operating Conditions

Storage capacity of the system is dependent on the temperature of the source and sink. The operating conditions assumed should be conservative in terms of the sizing of the various storage components. However, the cost of the system is dramatically affected by the use of atmospheric storage vessels for the water and particularly for the acid. If it is found necessary to replace the inexpensive tank used with a more expensive corrosion resistant tank due to higher than anticipated temperatures in this tank, the cost of the system will increase dramatically.

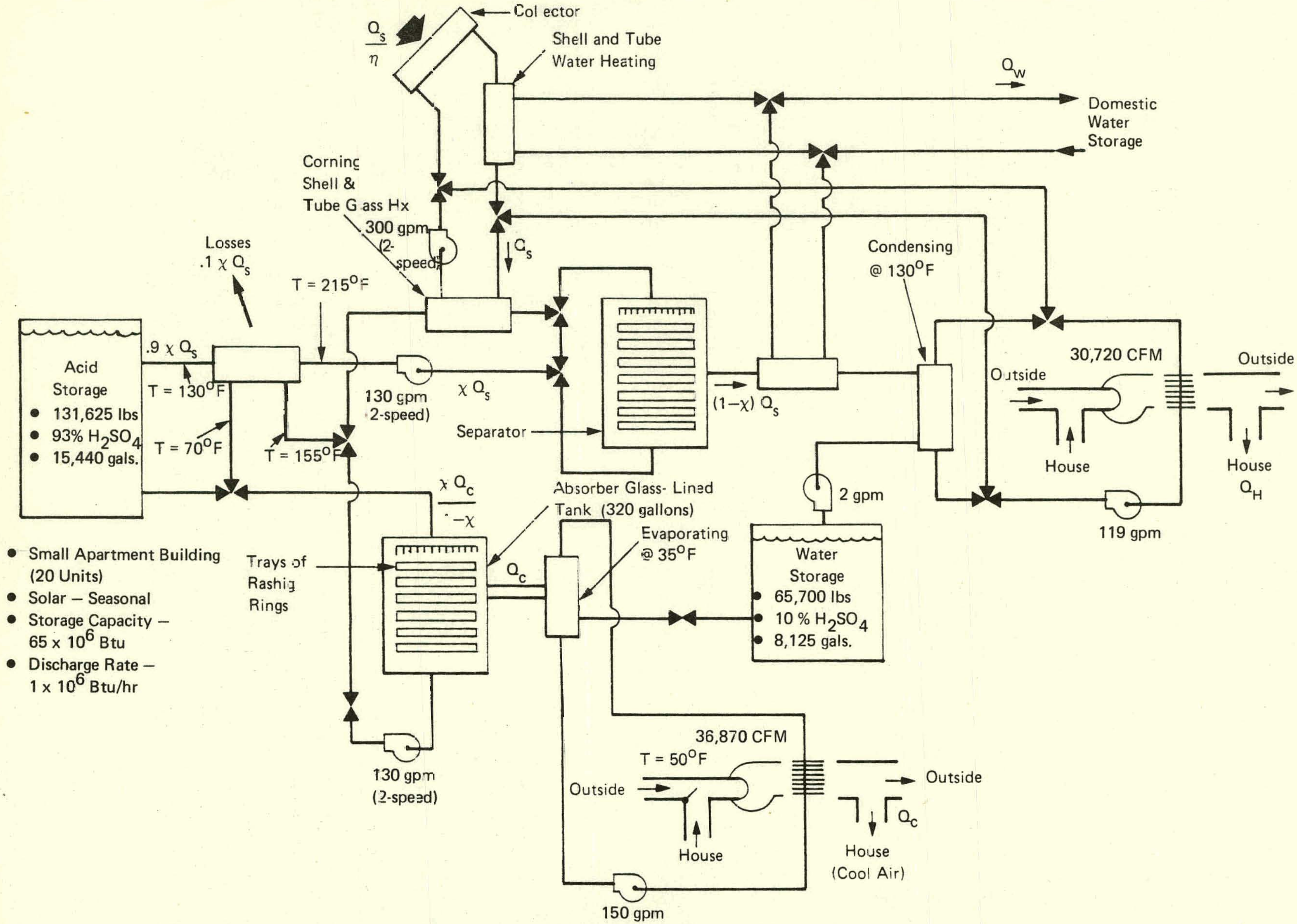


FIGURE 4–6 ROCKET RESEARCH (CONFIGURATION #1)

TYPE: CHEMICAL HEAT PUMP

CONTRACTOR: Rocket Research Corporation (Code #4)

INPUT: Solar

CYCLE: Seasonal

STORAGE CAPACITY: 65×10^6 Btu

DISCHARGE RATE: 1×10^6 Btu/hr

			(%)
STORAGE MEDIUM	A	$ 4277	4.0
CONTAINER	B	21497	20.0
INSULATION	C	50	.05
HEAT EXCHANGERS	D	46820	43.7
FLUID	E	250	0.2
PIPING AND DUCTING	F	5040	4.7
BLOWER & MOTOR	G	5642	5.3
PUMP & MOTOR	H	5520	5.2
CONTROLS	I	6421	6.0
INSTALLATION COST	J	11,661	10.9
SYSTEM COST		107,178	100%
COST OF MAINTENANCE PER YEAR		7025	
NO. OF SYSTEMS PER YEAR		1000	

Table 4-4

COST SUMMARY - ROCKET RESEARCH (CONFIGURATION 1)

4.2.5 Rocket Research (Configuration 2)

- Application

This system (see Figure 4-7) is sized to meet 100% of residential heating, cooling and water heating loads using solar inputs and seasonal storage.

- System Description

This system is similar to that described in Section 4.2.4 except that the HVAC system has been resized to provide heating and cooling at a rate consistent with residential use and the amount of storage is less. Cost estimates are given in Table 4-5.

- Installation

We assumed that these systems would be installed indoors.

- Operating Conditions

Storage capacity of the system is dependent on the temperature of the source and sink. The operating conditions assumed should be conservative in terms of the sizing of the various storage components. However, the cost of the system is dramatically affected by the use of atmospheric storage vessels for the water and particularly for the acid. If it is found necessary to replace the inexpensive tank used with a more expensive corrosion resistant tank due to higher than anticipated temperatures in this tank, the cost of the system will increase dramatically.

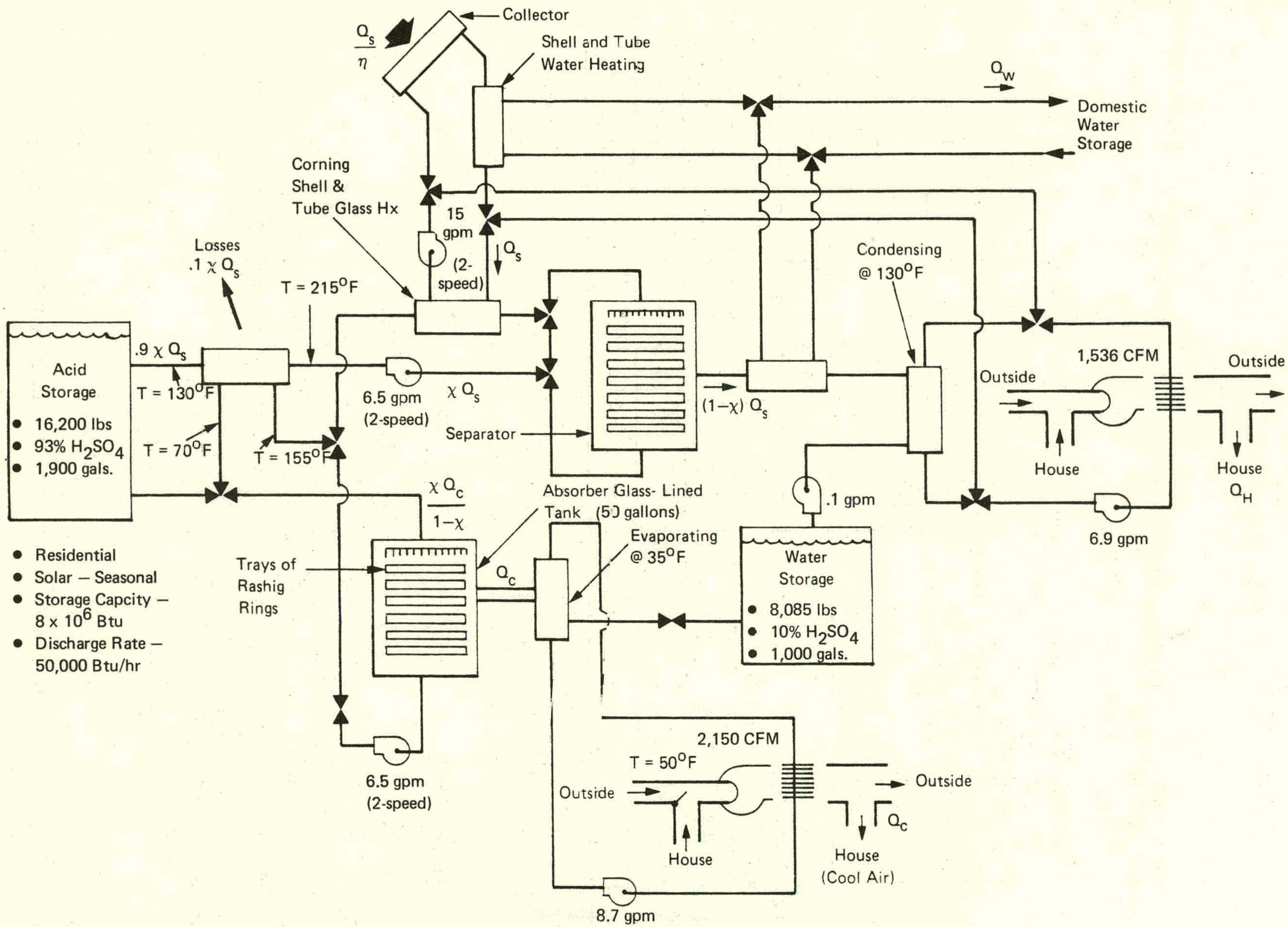


FIGURE 4–7 ROCKET RESEARCH (CONFIGURATION #2)

TYPE: CHEMICAL HEAT PUMP

CONTRACTOR: Rocket Research (Code #5)

INPUT: Solar

CYCLE: Seasonal

STORAGE CAPACITY: 8×10^6 Btu

DISCHARGE RATE: 50,000 Btu/hr Heating and Cooling

			(%)
STORAGE MEDIUM	A	$ 526	2.1
CONTAINER	B	4598	18.4
INSULATION	C	36	0.1
HEAT EXCHANGERS	D	4249	17.0
FLUID	E	34	0.1
PIPING AND DUCTING	F	1165	4.7
BLOWER & MOTOR	G	1224	4.9
PUMP & MOTOR	H	2715	10.9
CONTROLS	I	5098	20.4
INSTALLATION COST	J	5369	21.5
SYSTEM COST		25014	100%
COST OF MAINTENANCE PER YEAR		1431	
NO. OF SYSTEMS PER YEAR		1000	

Table 4-5

COST SUMMARY - ROCKET RESEARCH (CONFIGURATION 2)

4.2.6 Rocket Research (Configuration 3)

• Application

This system (see Figure 4-8) was sized to provide diurnal space heating and cooling plus water heating for a small apartment building using solar input. The capacity shown should be appropriate for meeting 50% of the load.

• System Description

This system is functionally similar to the system described in Section 4.2.4.

In this case, because the system operates with diurnal storage, we assumed that the storage tanks would cycle through a high temperature and thus that more expensive glass lined tanks would be required. Cost estimates for the system are given in Table 4-6.

• Installation:

It was assumed that this system would be installed indoors.

• Operating Conditions:

Storage capacity of the system is dependent on the temperature of the source and sink. The operating conditions assumed should be conservative in terms of the sizing of the various storage components. However, the cost of the system is dramatically affected by the use of atmospheric storage vessels for the water and particularly for the acid. If it is found necessary to replace the inexpensive tank used with a more expensive corrosion resistant tank due to higher than anticipated temperatures in this tank, the cost of the system will increase dramatically.

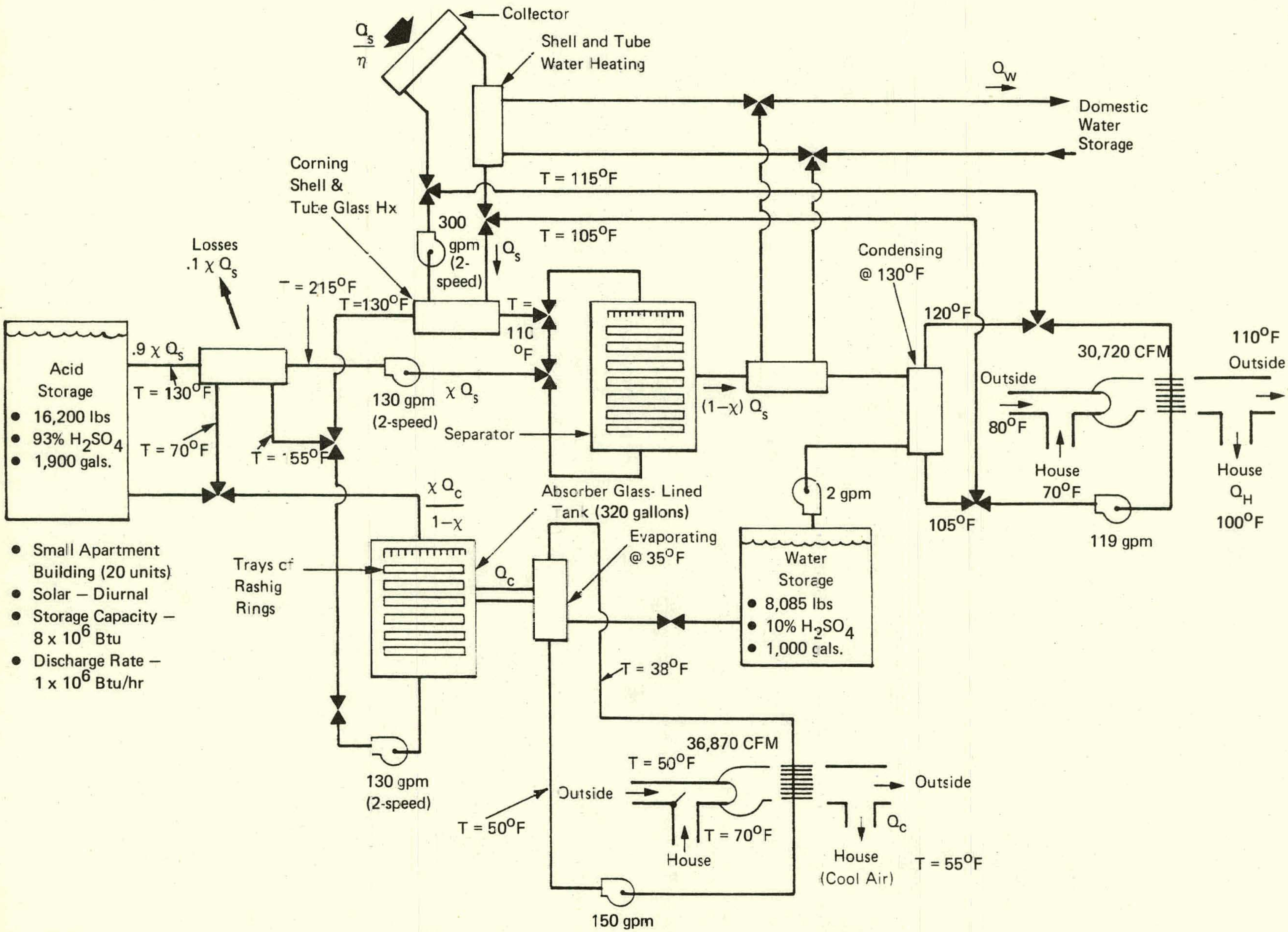


FIGURE 4–8 ROCKET RESEARCH (CONFIGURATION #3)

TYPE: CHEMICAL HEAT PUMP

CONTRACTOR: Rocket Research (Code #6)

INPUT: Solar

CYCLE: Diurnal

STORAGE CAPACITY: 8×10^6 Btu

DISCHARGE RATE: 1×10^6 Btu/hr Heating

			(%)
STORAGE MEDIUM	A	$ 526	0.6
CONTAINER	B	21320	22.5
INSULATION	C	232	0.2
HEAT EXCHANGERS	D	43554	46.0
FLUID	E	250	0.3
PIPING AND DUCTING	F	4540	4.8
BLOWER & MOTOR	G	5642	6.0
PUMP & MOTOR	H	5520	5.8
CONTROLS	I	6421	6.8
INSTALLATION COST	J	6685	7.1
SYSTEM COST		94690	100%
COST OF MAINTENANCE PER YEAR		6717	
NO. OF SYSTEMS PER YEAR		6000	

Table 4-6

COST SUMMARY - ROCKET RESEARCH
(Configuration 3)

4.2.7 Rocket Research (Configuration 4)

- Application

The system (see Figure 4-9) is sized to provide 50% of residential space heating, cooling, and water heating loads using solar input with diurnal storage.

- System Description

This system is functionally similar to the system described in Section 4.2.6. As with the commercial diurnal storage system we assumed that the storage tanks would cycle to a temperature of 400° and thus that a glass lined tank would be required. The HVAC system is sized for a residence. Cost estimates are presented in Table 4-7.

- Installation

We assumed that this system would be installed indoors.

- Operating Conditions

See Section 4.2.4.

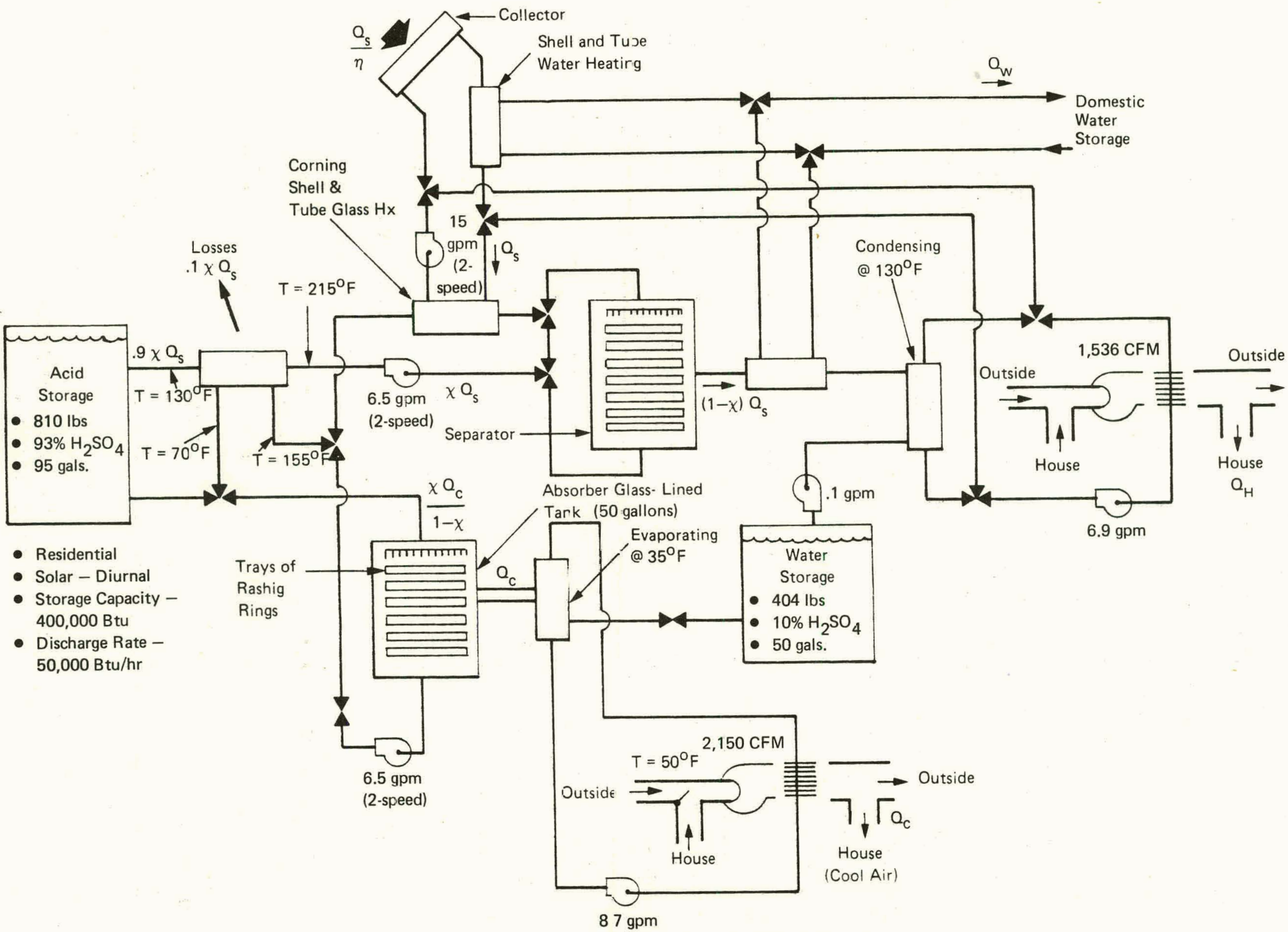


FIGURE 4–9 ROCKET RESEARCH (CONFIGURATION #4)

TYPE: CHEMICAL HEAT PUMP

CONTRACTOR: Rocket Research (Code #7)

INPUT: Solar

CYCLE: Diurnal

STORAGE CAPACITY: 400,000 Btu

DISCHARGE RATE: 50,000 Btu/hr

			(%)
STORAGE MEDIUM	A	$ 26	0.1
CONTAINER	B	2008	10.1
INSULATION	C	47	0.2
HEAT EXCHANGERS	D	3655	18.4
FLUID	E	34	0.2
PIPING AND DUCTING	F	1165	5.9
BLOWER & MOTOR	G	1224	6.2
PUMP & MOTOR	H	2715	13.7
CONTROLS	I	5098	25.7
INSTALLATION COST	J	3859	19.5
SYSTEM COST		19831	100%
COST OF MAINTENANCE PER YEAR		1090	
NO. OF SYSTEMS PER YEAR		36000	

Table 4-7

COST SUMMARY - ROCKET RESEARCH
(Configuration 4)

4.2.8 University of Delaware (Configuration 1)

- Application

This system stores coolness developed from electrical input during a diurnal cycle (see Figure 4-10). The system is sized for small buildings or residences. In this application, off-peak electricity is used to cool down a storage device at night. During the day, coolness could be extracted from storage to provide air conditioning.

- System Description

A eutectic mixture which contains sodium sulphate decahydrate modified by the addition of sodium chloride and potassium chloride so that it melts at 55°F is used as the storage medium. This is cycled through a temperature range from 40 to 60°F to provide the required coolness storage.

The mixture is packaged in long cylindrical plastic chubs 2" in diameter and 22" long. These chubs are supported in self stacking racks which contain 11 chubs per unit. Air passes over the surface of the plastic material which serves both to contain the heat storage material and to provide heat exchange contact between the heat storage material and air which is used as the heat transfer fluid. Cost estimates for this system are given in Table 4-8.

- Installation

This system is assembled at the site, utilizing plastic chubs which have been filled with storage material at the factory and put into the self stacking plastic racks for shipment. Each rack containing 11 chubs weighs approximately 40 lbs. During the assembly process the contractor takes the chubs and racks which have been purchased as a separate item, stacks the racks to obtain the appropriate shape, fabricates a plywood enclosure using plywood purchased locally, insulates the enclosure using locally purchased insulation, installs inlet and outlet air ducts and temperature control devices, and encloses the complete package with a second layer of plywood to cover the insulation. In some cases, a separate foundation must be provided to support the heat storage unit.

- Operating Conditions

The surface area of the chubs gives adequate heat transfer to cool at an acceptable rate. However, the melting point at 55°F is higher than suitable for providing dehumidification of conditioned air. University of Delaware personnel believe that the dehumidification which occurs at night during charging of the system provides adequate daytime humidity levels.* Typical HVAC practice requires a 45° coil in contact with the

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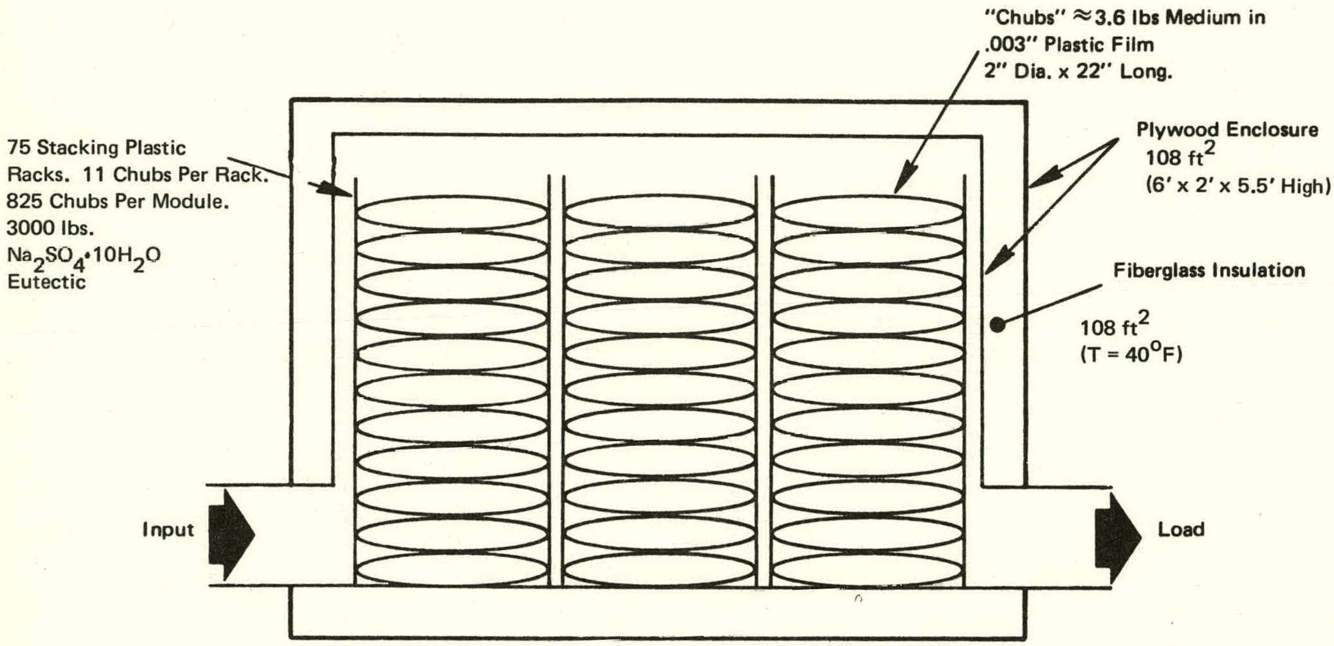
* G.R. Frysinger, J. Slinkowski, and A.M. Barnett, "Commercialization of Storage-Assisted Air Conditioning Using Phase Change Materials," ASHRAE, Winter Meeting, 1979.



- Residence
- Storage Capacity: 200,000 Btu
- Discharge Rate; 35,000 Btu/hr
- Off-Peak Electric Cooling

FIGURE 4–10 UNIVERSITY OF DELAWARE (CONFIGURATION # 1) (CODE # 18) air being cooled in order to provide for dehumidification. If a eutectic with a lower melting point were used in the present configuration so that humidification did occur, the system would have to be redesigned in order to provide a mechanism for removing the condensation as it collected on the heat transfer surfaces. In addition, the buildup of condensation might require additional heat transfer surface, due to the limiting effect of the moisture on the surface.

TYPE: PHASE CHANGE MATERIAL

CONTRACTOR: University of Delaware (Code #8)

INPUT: Electric

CYCLE: Diurnal

STORAGE CAPACITY: 200,000 Btu

DISCHARGE RATE: 35,000 Btu/hr Cooling

			(%)
STORAGE MEDIUM	A	$ 60	9.3
CONTAINER	B	242	37.7
INSULATION	C	15	2.3
HEAT EXCHANGERS	D	-	-
FLUID	E	-	-
PIPING AND DUCTING	F	-	-
BLOWER & MOTOR	G	-	-
PUMP & MOTOR	H	-	-
CONTROLS	I	70	11
INSTALLATION COST	J	255	39.7
SYSTEM COST		642	100%
COST OF MAINTENANCE PER YEAR		33.30	
NO. OF SYSTEMS PER YEAR		90,000	

Table 4-8

COST SUMMARY - UNIVERSITY OF DELAWARE (CONFIGURATION 1)

4.2.9 Franklin Institute System

The Franklin Institute System utilizes off-peak electrical energy to generate coolness which is stored for residences on a diurnal basis.

- System Description

This method (see Figure 4-11) employs crystallizing and dissolving phase change media in water, using materials which dissolve endothermally and have large coefficients of solubility with temperature. Energy transfer occurs by circulating oil which is cooled through this water-based storage medium. The oil in this case is immiscible and droplets which are formed float through the heat storage solution and return to the top of the tank where they are separated and recirculated. A cooling coil in the top of the tank cools the oil to charge the system. The system is discharged by circulating the oil through a heat exchanger external to the thermal energy storage module where it is heated and returned through the heat storage medium to be cooled again.

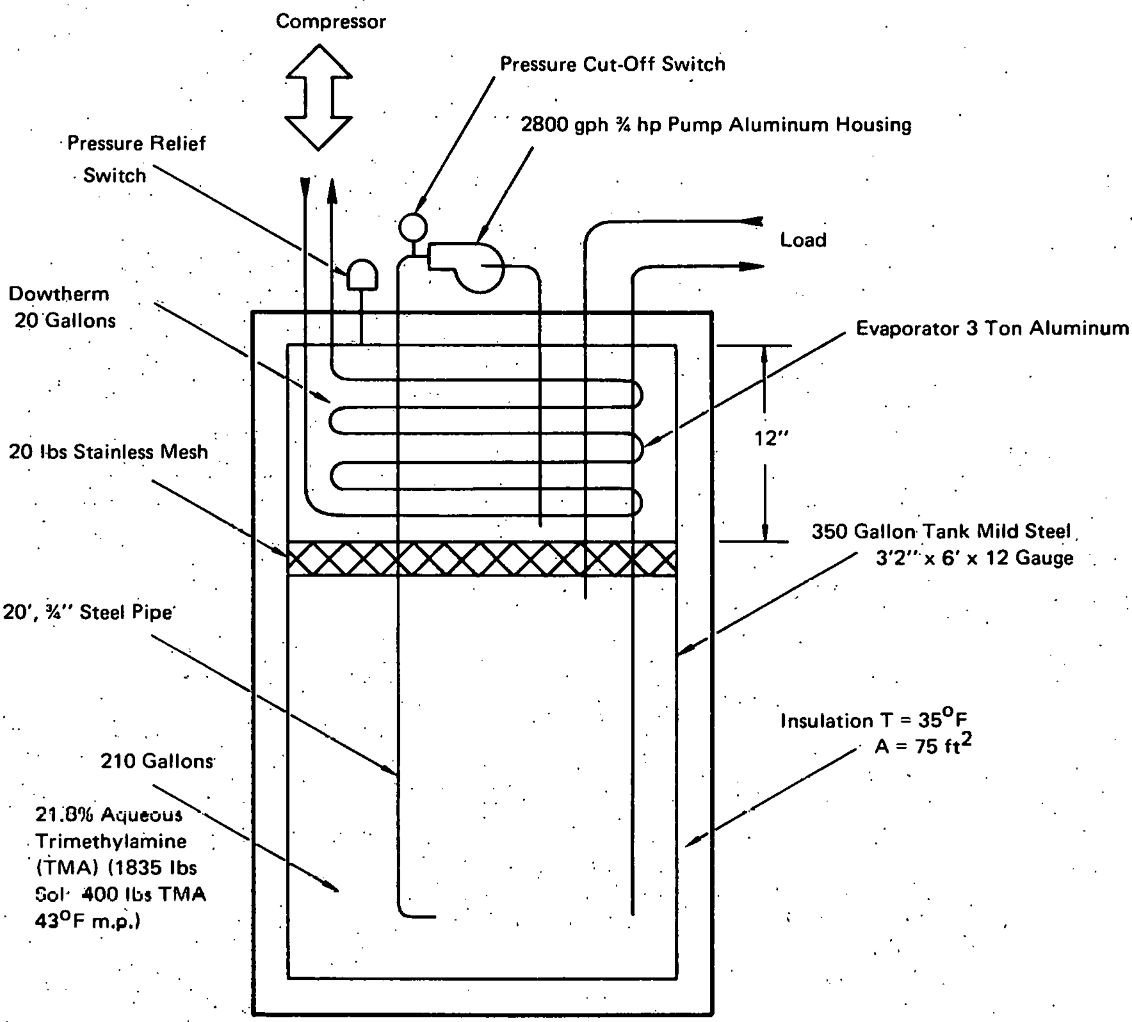
The system consists of a 350 gallon mild steel tank which has been insulated. Because the system operates at atmospheric pressure and the tank does not require a coating, a thin gauge steel tank can be used. A standard evaporator coil with a three ton capacity is positioned in the top of the tank. During charging this coil is used to cool the Dowtherm which collects at the top of the tank. A circulating pump forces the Dowtherm into the bottom of the tank where it passes through a nozzle which generates a large number of small droplets. These droplets pass through a diffuser and float through the heat storage material, trimethylamine, to the top of the tank, thereby cooling the heat storage material. Cost estimates are given in Table 4-9.

- Installation

This system was costed assuming that the complete unit charged with heat storage material with appropriate controls and circulating pump was factory assembled and shipped to the site. Thus, the only field installation required was a hook-up of lines to the compressor and to the duct heat exchanger plus normal wiring which would be similar to that involved in installing an air conditioning system.

- Operating Conditions

During operation, this device should provide adequate cooling, both in terms of the temperature of the cooling media in the air duct coil and in terms of delivery rates. The major operating question relates to whether the formation of an emulsion between the oil and the storage solution can be avoided by the use of a stainless steel mesh separating the two materials. Should an emulsion form which limits the performance of the system, it will be necessary to provide a mechanism for recharging the system periodically with fresh material. This cost would have to be considered as part of the maintenance of the system. Since trimethylamine solutions are toxic and volatile, outside location is preferred. Also, the melted medium cannot be used directly in a fan coil.



- Residence
- Storage Capacity: 200,000 Btu
- Discharge Rate: 35,000 Btu/hr
- Off-Peak, Electric Space Cooling

FIGURE 4–11 FRANKLIN INSTITUTE (CODE #9)

TYPE: PHASE CHANGE MATERIALS

CONTRACTOR: Franklin Institute (Code #9)

INPUT: Electric

CYCLE: Diurnal

STORAGE CAPACITY: 200,000 Btu

DISCHARGE RATE: 35,000 Btu/hr Cooling

			(%)
STORAGE MEDIUM	A	$ 128	8.6
CONTAINER	B	246	16.5
INSULATION	C	11	.7
HEAT EXCHANGERS	D	100	6.7
FLUID	E	98	6.6
PIPING AND DUCTING	F	6	.4
BLOWER & MOTOR	G	-	-
PUMP & MOTOR	H	386	26
CONTROLS	I	190	12.8
INSTALLATION COST	J	322	21.7
SYSTEM COST		1,487	100%
COST OF MAINTENANCE PER YEAR		109	
NO. OF SYSTEMS PER YEAR		90,000	

Table 4-9

COST SUMMARY - FRANKLIN INSTITUTE

4.2.10 Dow Chemical (Configuration 1)

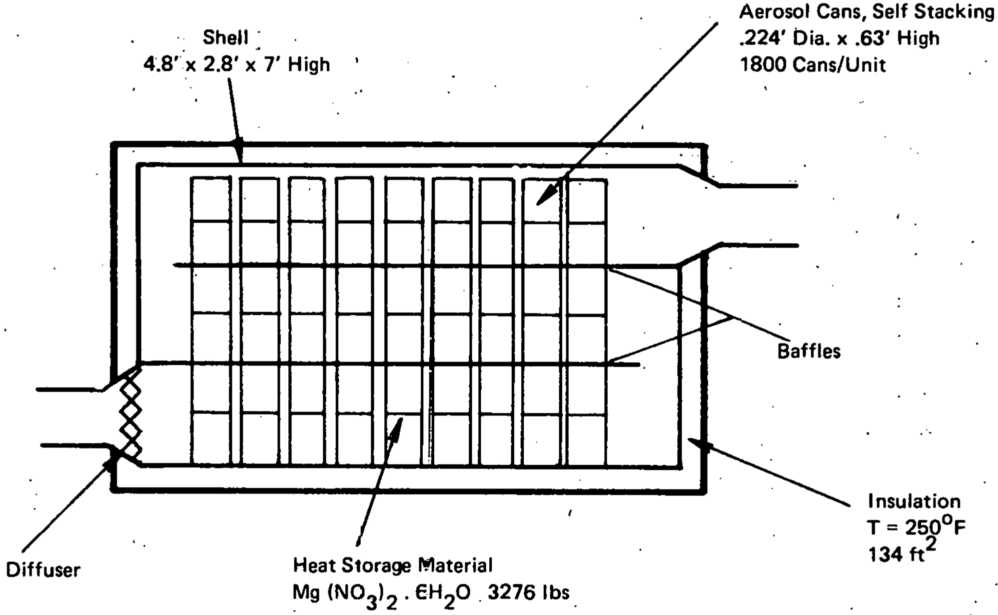
Shown in Figure 4-12, this system utilizes a phase change material to store off-peak electricity in the form of heat for use in space heating of residences.

- System Description

This system utilizes a mixture of magnesium nitrate hexahydrate as the heat storage medium. This medium is contained in self stacking aerosol cans, approximately 2-3/4" in diameter by 7-1/2" tall. 3,600 of these cans are required for the system storage capacity specified for residential heating. These cans are stacked 7 rows high with a baffle as required to provide a multi-pass air flow through the unit. A sheet metal housing encloses the cans and provides for support of the system. It was assumed in the design that the baffles were attached to the external housing and the housing was supported rigidly so that by stacking the cans on top of the baffle and on top of each other, the system would be strong enough to maintain the spacing once the cans had been placed properly. The system was insulated and surrounded with a second sheet metal housing. In operation, hot air is blown through the system to charge it and room air is passed through the system, as required, for space heating. Cost estimates are given in Table 4-10.

- Installation

In the costing of the system it was assumed that it would be assembled on site, rather than assembled at the factory and shipped as a unit. This assumption was made because the assembled weight of the unit is so large that it could only be handled by riggers if it was shipped as a single unit. In addition, the reinforcing necessary to make it structurally strong enough to be shipped assembled would have added significantly to the cost of the system. The configuration described above assumes that as the unit is built at the site the reinforcing of the sheet metal housing will be sufficient to hold the cans in place since the only force on them will be air flowing through the system. During the installation, the base of the system will be put in position. Next, columns two cans high will be placed at appropriate intervals on the base, and a baffle would be placed on top of the cans and attached to one side of the supporting structure. Three more layers of cans will be stacked up, a second baffle put in place, and finally two more rows of cans added to the top. The system will then be screwed together with sheet metal screws and bolts as required to assemble the support angles to the sheet metal housing. Next, the insulation will be applied to the outside and a sheet metal housing installed.



- Residence
- Storage Capacity: 400,000 Btu
- Discharge Rate: 30,000 Btu/hr
- Off-Peak, Electric Space Heating (Diurnal)

FIGURE 4–12 DOW CHEMICAL (CONFIGURATION # 1) (CODE # 10)

TYPE: PHASE CHANGE MATERIALS

CONTRACTOR: Dow Chemical (Code #10)

INPUT: Electric

CYCLE: Diurnal

STORAGE CAPACITY: 400,000 Btu

DISCHARGE RATE: 30,000 Btu/hr Heating

			(%)
STORAGE MEDIUM	A	$ 524	33.1
CONTAINER	B	683	43.1
INSULATION	C	40	2.5
HEAT EXCHANGERS	D	-	-
FLUID	E	-	-
PIPING AND DUCTING	F	-	-
BLOWER & MOTOR	G	-	-
PUMP & MOTOR	H	-	-
CONTROLS	I	70	4.4
INSTALLATION COST	J	266	16.8
SYSTEM COST		1583	100%
COST OF MAINTENANCE PER YEAR		54	
NO. OF SYSTEMS PER YEAR		40,000	

Table 4-10

COST SUMMARY - DOW CHEMICAL (CONFIGURATION 1)

- Operating Conditions

Output curves for this system indicate that the capacity indicated for the amount of storage material shown is accurate and that the delivery temperature is acceptable for standard space heating systems. The only operating limitation appears to be the delivery rate. We feel that to provide adequate system response for a typical space heating system, a delivery rate of 50,000 Btu's per hour for a typical residence requiring this kind of a device is minimal. The cost of the DOW System would be increased, if it were necessary to provide surface area to deliver energy at this increased rate, as the system with the given surface to volume ratio will only deliver at a rate of 30,000 Btu's per hour.

4.2.11 Dow Chemical (Configuration 2)

- Application

In this system solar energy is stored for heating of residences using a diurnal cycle.

- Storage Mechanism

The system in this case (see Figure 4-13) is similar to that described in Section 4.2.10. The only difference is that more cans are required and a different heat storage material is utilized. In this case, the heat storage material (magnesium nitrate hydrate plus ammonia nitrate) melts at a temperature of 126°F. Cost estimates are given in Table 4-11.

- System Description

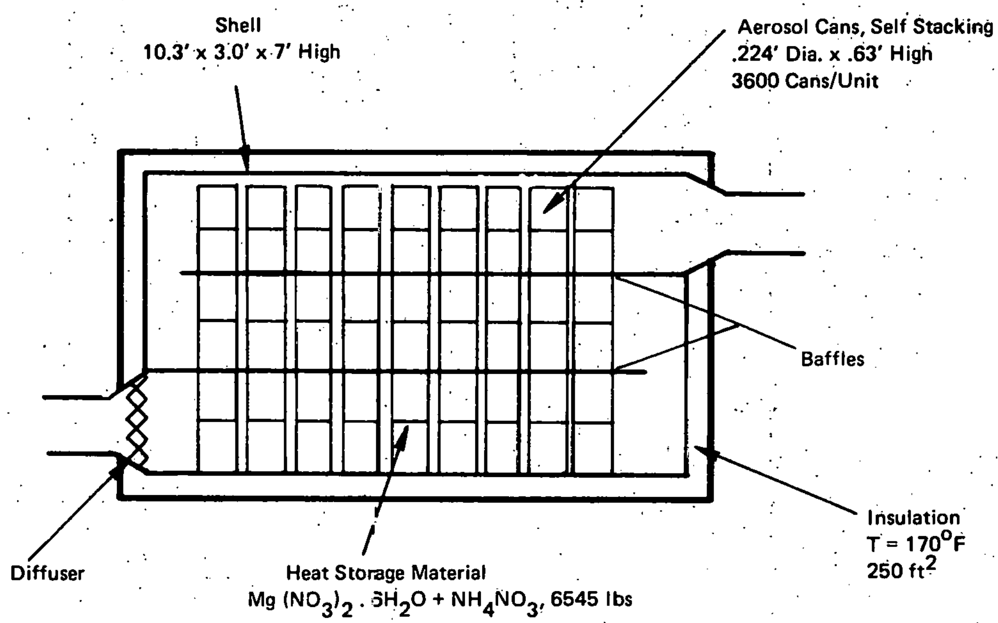
(See Section 4.2.10)

- Installation

(See Section 4.2.10)

- Operating Characteristics

(See Section 4.2.10)



- Residence
- Storage Capacity: 400,000 Btu
- Discharge Rate: 30,000 Btu/hr
- Solar Space Heating (Diurnal)

FIGURE 4–13 DOW CHEMICAL (CONFIGURATION # 2) (CODE # 11)

TYPE: PHASE CHANGE MATERIAL

CONTRACTOR: Dow Chemical (Code #11)

INPUT: Solar

CYCLE: Diurnal

STORAGE CAPACITY: 400,000 Btu

DISCHARGE RATE: 30,000 Btu/hr Heating

			(%)
STORAGE MEDIUM	A	$ 720	28.7
CONTAINER	B	1307	52.0
INSULATION	C	50	2.0
HEAT EXCHANGERS	D	-	-
FLUID	E	-	-
PIPING AND DUCTING	F	-	-
BLOWER & MOTOR	G	-	-
PUMP & MOTOR	H	-	-
CONTROLS	I	70	2.9
INSTALLATION COST	J	365	14.5
SYSTEM COST		2512	100%
COST OF MAINTENANCE PER YEAR		77	
NO. OF SYSTEMS PER YEAR		36,000	

Table 4-11

COST SUMMARY - DOW CHEMICAL (CONFIGURATION 2)

4.2.12 Clemson University

- Application

This system is designed to provide space heating to residences using solar input on a diurnal basis. The system could also be designed for use as an off-peak electric storage system using either resistance or heat pump input.

- System Description

In the system shown in Figure 4-14 the heat transfer fluid is circulated through the thermal storage medium as dispersed droplets due to a diffuser fitted into the base of the storage tank. Heat is added to or removed from the system by direct contact of two immiscible fluids. The heat storage material (sodium thiosulfate) is an aqueous solution which has a substantial heat of crystallization that occurs at 118°F. An external pump circulates Exxon Marcol 72 through an external heat exchanger and then through the heat storage tank either heating the heat storage material or extracting heat from the heat storage material depending on the operating mode.

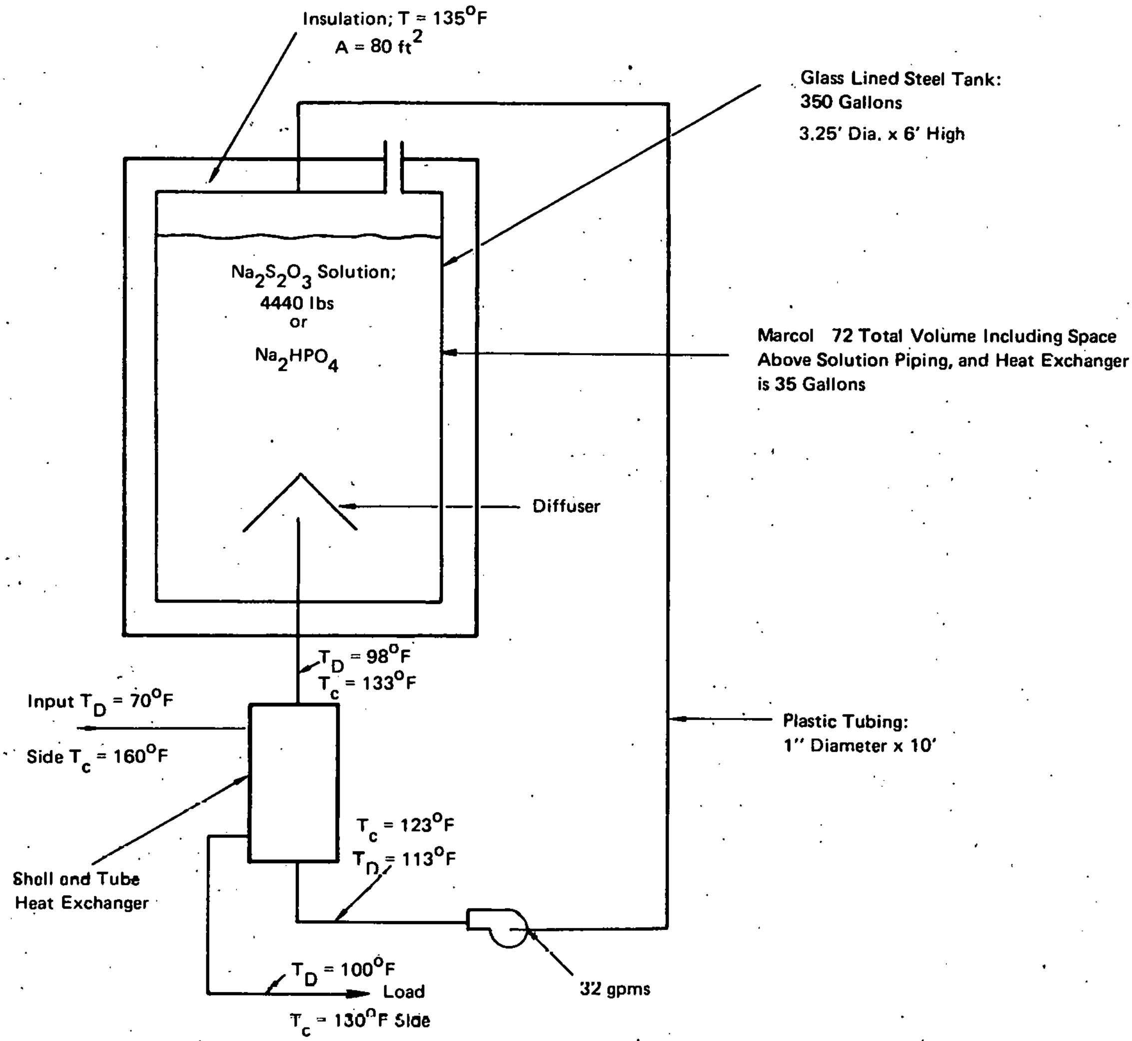
The system consists of a 355 gallon glass lined steel tank which contains the heat storage solution. Heat exchanger and pump are mounted with the tank and the unit is shipped as a single device. Costs estimates are presented in Table 4-12.

- Installation

Installation in this case involves simply attaching the heat transfer systems from the load and input to the heat exchanger which is external to the system and bringing power to a control box mounted on the device.

- Operating Characteristics

This system delivers energy at a sufficient rate and temperature for normal HVAC system conditions. The major question concerning its long term operation as with the Franklin Institute System is whether mixing between the two fluids will eventually form an emulsion. If the unit has a limited operating life due to a break-down or a mixing of the two fluids which require that they be changed periodically, this must be accounted for in the routine maintenance of the system and must be allowed for in the design of the hardware.



T_D = Temperatures During Discharging
T_c = Temperatures During Charging

- Residence
- Storage Capacity 400,000 Btu
- Discharge Capacity 50,000 Btu/hr
- Solar Space Heating (Diurnal)

FIGURE 4–14 CLEMSON UNIVERSITY (CODE # 12)

TYPE: PHASE CHANGE MATERIALS

CONTRACTOR: Clemson University (Code #12)

INPUT: Solar

CYCLE: Diurnal

STORAGE CAPACITY: 400,000 Btu

DISCHARGE RATE: 50,000 Btu/hr Heating

			(%)
STORAGE MEDIUM	A	$ 533	19.9
CONTAINER	B	363	13.5
INSULATION	C	14	0.5
HEAT EXCHANGERS	D	840	31.3
FLUID	E	44	1.6
PIPING AND DUCTING	F	2	–
BLOWER & MOTOR	G	–	–
PUMP & MOTOR	H	386	14.4
CONTROLS	I	180	6.7
INSTALLATION COST	J	322	12.0
SYSTEM COST		2684	100%
COST OF MAINTENANCE PER YEAR		354	
NO. OF SYSTEMS PER YEAR		36,000	

Table 4-12

COST SUMMARY - CLEMSON UNIVERSITY

4.2.13 University of Delaware (Configuration 2)

- Application:

In this application heating of a residence is provided on a diurnal basis by solar input to a storage system.

- System Description:

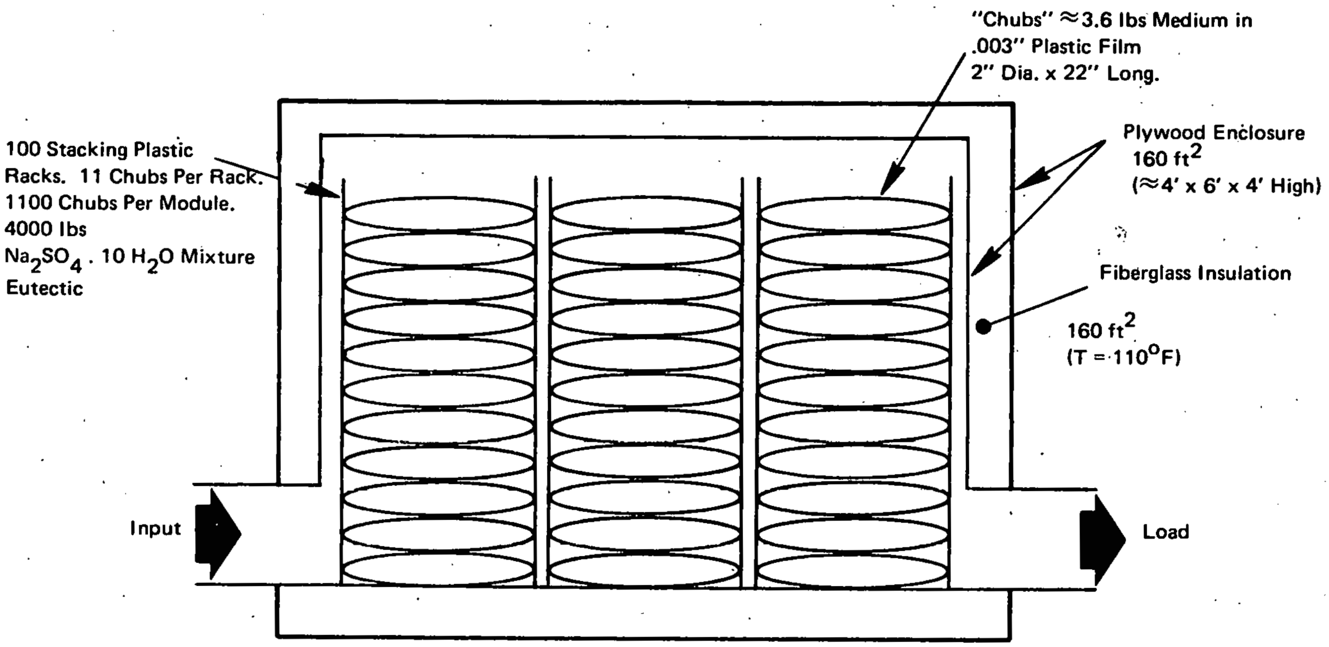
This system utilizes the configuration described in Section 4.2.8 (see Figure 4-15). In this case, sodium sulfate decahydrate is used without melting point depressants to provide space heating rather than space cooling. The heat storage material melts at a temperature of approximately 88°F. The system utilizes 3,700 lbs of sodium sulphate decahydrate mixture contained in 1,100 chubs mounted in racks and stacked as described earlier. Cost estimates are given in Table 4-13.

- Installation:

The installation of the system is the same as described in Section 4.2.8.

- Operating Characteristics:

The low melting point of the heat storage material in this case will only provide delivered air at a temperature of between 80 and 85°F depending on the state of the charge of the system. It will, however, deliver at a rate sufficient to heat a normal dwelling. However, the air flow rate required to deliver the energy at a sufficient Btu/hr rate is too high for a normal dwelling. Larger blowers and ducts would be required than in a normal installation and air currents through a room might be objectionably high due to the circulation rate.



- Residence
- Storage Capacity: 400,000 Btu
- Delivery Rate: 50,000 Btu/hr
- Solar Space Heating (Diurnal)

FIGURE 4–15 UNIVERSITY OF DELAWARE (CONFIGURATION # 2) (CODE # 13)

TYPE: PHASE CHANGE MATERIALS

CONTRACTOR: University of Delaware (Code #13)

INPUT: Solar

CYCLE: Diurnal

STORAGE CAPACITY: 400,000 Btu

DISCHARGE RATE: 50,000 Btu/hr Heating

			(%)
STORAGE MEDIUM	A	$ 81	9.9
CONTAINER	B	319	38.8
INSULATION	C	22	2.7
HEAT EXCHANGERS	D	-	-
FLUID	E	-	-
PIPING AND DUCTING	F	-	-
BLOWER & MOTOR	G	-	-
PUMP & MOTOR	H	-	-
CONTROLS	I	70	8.5
INSTALLATION COST	J	330	40.1
SYSTEM COST		822	100%
COST OF MAINTENANCE PER YEAR		43	
NO. OF SYSTEMS PER YEAR		36,000	

Table 4-13

COST SUMMARY - UNIVERSITY OF DELAWARE (CONFIGURATION 2)

4.2.14 Monsanto Research System

- Application

This system provides for heating and cooling of a residence, using solar input on a diurnal basis. The system is designed to operate at storage temperatures between 250 and 285°F.* Cooling of the building will be done utilizing an absorption air conditioner. Heating will be provided directly using a liquid-to-air type heat exchanger.

- System Description

Form-stable polyethylene pellets which melt at approximately 265°F are utilized to store the energy in this case (see Figure 4-16). Heat is transferred into the system and out of the system using an ethylene glycol solution. Flow is downward through the system during charging and is reversed during discharging to maintain a thermal stratification in the polyethylene pellets. The tank in the system is a pressurized ASME pressure rated steel tank with the capacity of 450 gallons. An expansion tank is provided to allow for the expansion and contraction of the ethylene glycol and polyethylene during the heating and cooling cycle. Cost estimates are presented in Table 4-14.

- Installation

In costing this system it was assumed that the container would be shipped to the site, installed, and then charged with heat storage material.

- Operating Characteristics

This system should provide outputs for both heating and cooling at reasonable temperatures and rates.

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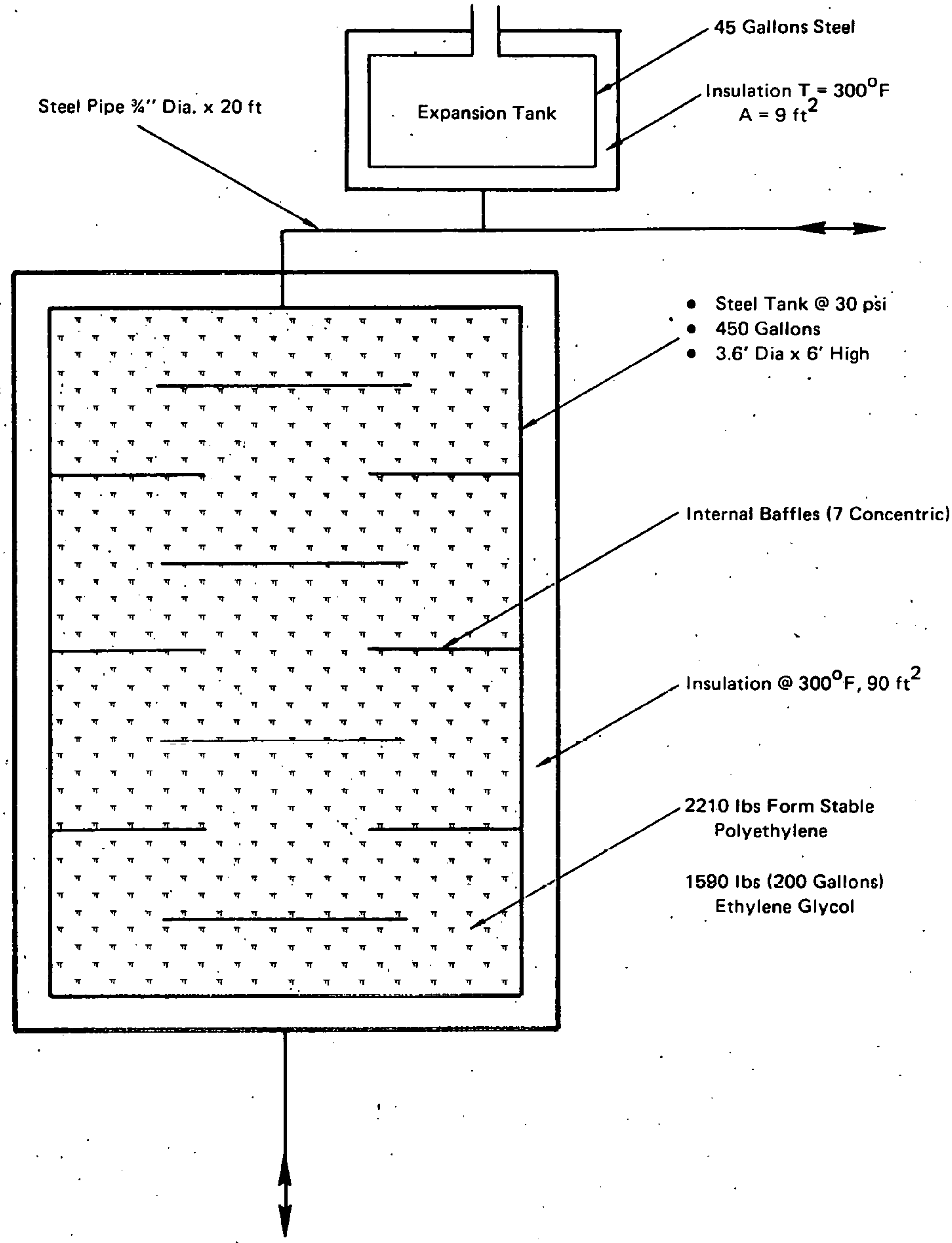
* "Form-Stable Crystalline Polymer Pellets for Thermal Energy Storage," ORO/5159-10 prepared by Monsanto Research Corporation for the U.S. Energy Research and Development Administration, July, 1977.



- Residence
- Storage Capacity
  - Heating: 400,000 Btu
  - Cooling: 250,000 Btu (Hot Side)*
- Discharge Rate
  - Heating: 50,000 Btu/hr
  - Cooling: 50,000 Btu/hr

*to Absorbtion Air Conditioner.

FIGURE 4–16 MONSANTO RESEARCH (CODE # 14)

TYPE: PHASE CHANGE MATERIALS

CONTRACTOR: Monsanto Research (Code #14)

INPUT: Solar

CYCLE: Diurnal

STORAGE CAPACITY: 400,000 Btu

DISCHARGE RATE: 50,000 Btu/hr Heating and Absorption Cooling

			(%)
STORAGE MEDIUM	A	$ 1,039	28.6
CONTAINER	B	2,261	62.3
INSULATION	C	35	1.0
HEAT EXCHANGERS	D	-	-
FLUID	E	-	-
PIPING AND DUCTING	F	6	.1
BLOWER & MOTOR	G	-	-
PUMP & MOTOR	H	-	-
CONTROLS	I	35	1.0
INSTALLATION COST	J	254	7.0
SYSTEM COST		3,630	100%
COST OF MAINTENANCE PER YEAR		176	
NO. OF SYSTEMS PER YEAR		1,000	

Table 4-14

COST SUMMARY - MONSANTO RESEARCH

4.2.15 Suntek System

- Application:

This system provides heating for residences using solar input on a diurnal basis. Energy is picked up from the sun as it is available and released without control to the dwelling (see Figure 4-17).

- System Description:

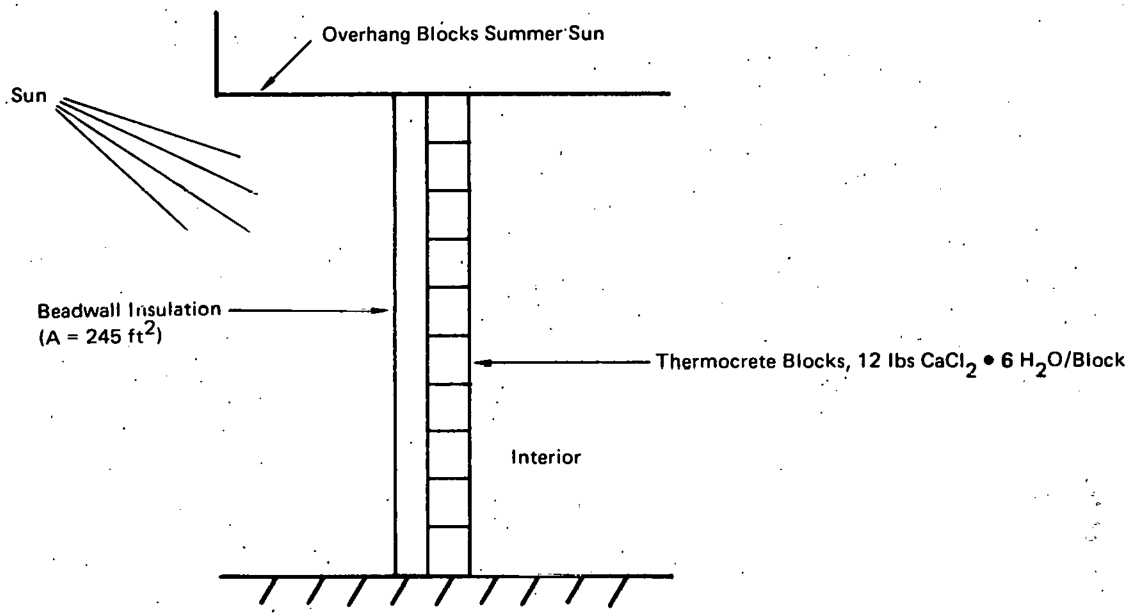
The Suntek blocks are fabricated using pumice blocks or low density foamed concrete blocks. First, these blocks are fitted with a tube and are coated with a urethane tar sealant or filled epoxy. Next, after the coating is cured, the block is evacuated, and heat storage material is injected back into the evacuated block utilizing the same tube. Finally, the tube is cut off and the hole sealed with a plastic plug. Each 8X8X16 concrete block stores approximately 1,450 Btu's which are liberated during the phase change between 74 and 79°F. Thus, for a storage capacity of 400,000 Btu's, a wall with 276 blocks would be required. A beadwall is used for insulating the system against nighttime losses. Costs for this system are estimated as shown in Table 4-15.

- Installation:

In costing the installation of this system we assumed that the blocks would be installed using butyl rubber compound applied in a bead on two surfaces of the block. Labor rates were based on the installation of face brick which cannot be chipped as opposed to concrete blocks which can be handled more roughly.

- Operating Conditions:

When used in a Trombe wall configuration where solar energy falls directly on the blocks and heats them to a temperature greater than the phase change temperature, this system will provide passive heating to the dwelling as the temperature of the dwelling falls below the phase change temperature. However, the rate at which heat is conducted through the blocks and transferred to the dwelling is comparatively low, so that the heat storage capacity of the system can only really be utilized over a period of several days. Therefore, on a daily basis, the effective storage capacity is less than the ideal capacity. Also, at night when heating is required, a back-up heat source may be necessary in order to maintain the dwelling at an acceptable temperature level.



- Each Block: 4" x 8" x 16", Stores 600 Btu in Phase Change At 74–79°F, Weights 30 lbs.
- Wall: 10' x 60' Contains 667 Blocks
- Heat Transfer by Natural Convention and Radiation

- Residence
- Storage Capacity: 400,000 Btu
- Discharge Rate: Variable ≈ 10,000 Btu/hr or Less
- Solar Heating (Diurnal)

FIGURE 4–17 SUNTEK (CODE # 15)

TYPE:	PHASE CHANGE MATERIALS
CONTRACTOR:	Suntek (Code #15)
INPUT:	Solar (Passive)
CYCLE:	Diurnal
STORAGE CAPACITY:	400,000 Btu
DISCHARGE RATE:	–

			(%)
STORAGE MEDIUM	A	$ 621	22.8
CONTAINER	B	–	–
INSULATION	C	1472	54.2
HEAT EXCHANGERS	D	–	–
FLUID	E	–	–
PIPING AND DUCTING	F	–	–
BLOWER & MOTOR	G	–	–
PUMP & MOTOR	H	–	–
CONTROLS	I	–	–
INSTALLATION COST	J	625	23
SYSTEM COST		2718	100%
COST OF MAINTENANCE PER YEAR		60	
NO. OF SYSTEMS PER YEAR		$30X10^6$ blocks	

Table 4-15

COST SUMMARY - SUNTEK

4.2.16 Brookhaven System

- Application:

The system shown in Figure 4-18 is designed to provide passive heating for a single family residence using solar input on a diurnal basis.

- System Description:

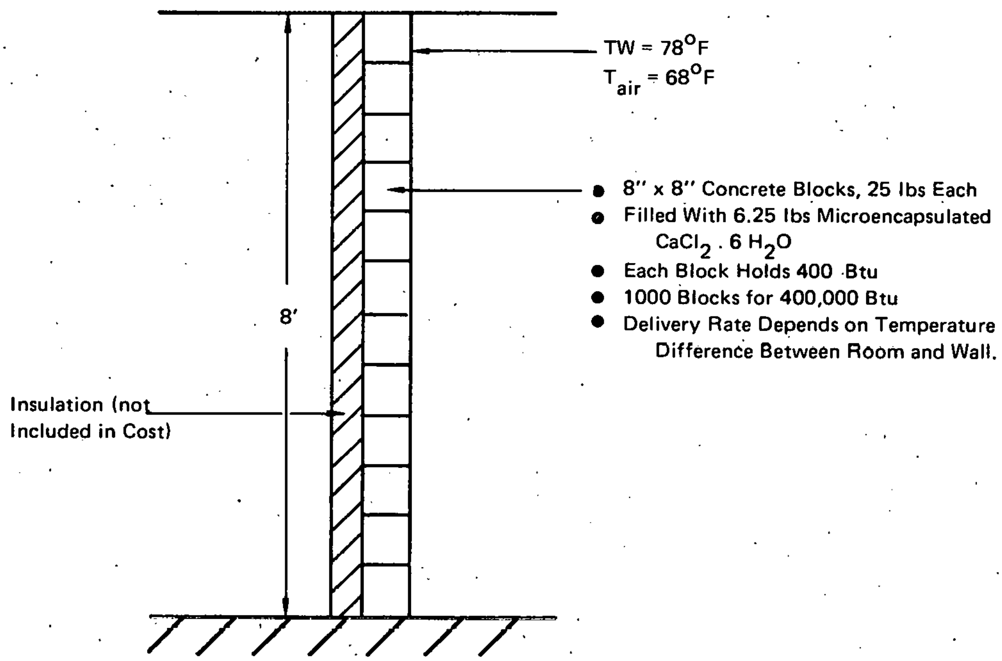
This system utilizes concrete blocks fabricated using microencapsulated heat storage material to replace some of the aggregate. Calcium chloride hydrate was used as the media for the system costed. Since each block has a capacity of approximately 400 Btu's, 1,000 blocks are required for a storage capacity of 400,000 Btu's. In this case, the system is charged from the inside, utilizing warm air in the building, rather than charged by the sun falling directly on the external surfaces of the block as in the Suntek System. This requires that the ambient air temperature on the inside of the building reach a temperature of 80° or more in order to provide adequate heat transfer to the blocks. The system is discharged automatically when the temperature of the building falls below the phase change temperature of approximately 75°F. An estimate of the cost of this system is given in Table 4-16.

- Installation:

For costing purposes, it was assumed that these blocks could be intalled using techniques suitable for standard concrete blocks. Installation costs include mortar and labor.

- Operating Conditions:

If this is used as a completely passive system, the temperature differential required for charging and discharging of this system implies that portions of the building are overheated during the day. As with the Suntek System, the delivery rate is low compared to the heat storage capacity of the blocks, so that it may not be possible to utilize the complete storage capacity over a single diurnal cycle.



- Residence
- Storage Capacity: 400,000 Btu
- Discharge Rate: Variable Btu/hr Probably Less Than 10,000
- Space Heating, Fossil Fuel Input (Diurnal)

FIGURE 4–18 BROOKHAVEN (CODE # 16)

TYPE: PHASE CHANGE MATERIALS

CONTRACTOR: Brookhaven National Laboratory (Code #16)

INPUT: Furnace (Passive)

CYCLE: Diurnal

STORAGE CAPACITY: 400,000 Btu

DISCHARGE RATE: –

			(%)
STORAGE MEDIUM	A	$ 4981	70.6
CONTAINER	B	—	—
INSULATION	C	—	—
HEAT EXCHANGERS	D	—	—
FLUID	E	—	—
PIPING AND DUCTING	F	—	—
BLOWER & MOTOR	G	—	—
PUMP & MOTOR	H	—	—
CONTROLS	I	—	—
INSTALLATION COST	J	2074	29.4
SYSTEM COST		7055	100%
COST OF MAINTENANCE PER YEAR		0	
NO. OF SYSTEMS PER YEAR		$30X10^6$ blocks	

Table 4-16

COST SUMMARY - BROOKHAVEN NATIONAL LABORATORY

4.2.17 Desert Reclamation (Configuration 1)

- Application:

This system provides cooling on a seasonal basis for a community size installation using input from the environment.

- System Description:

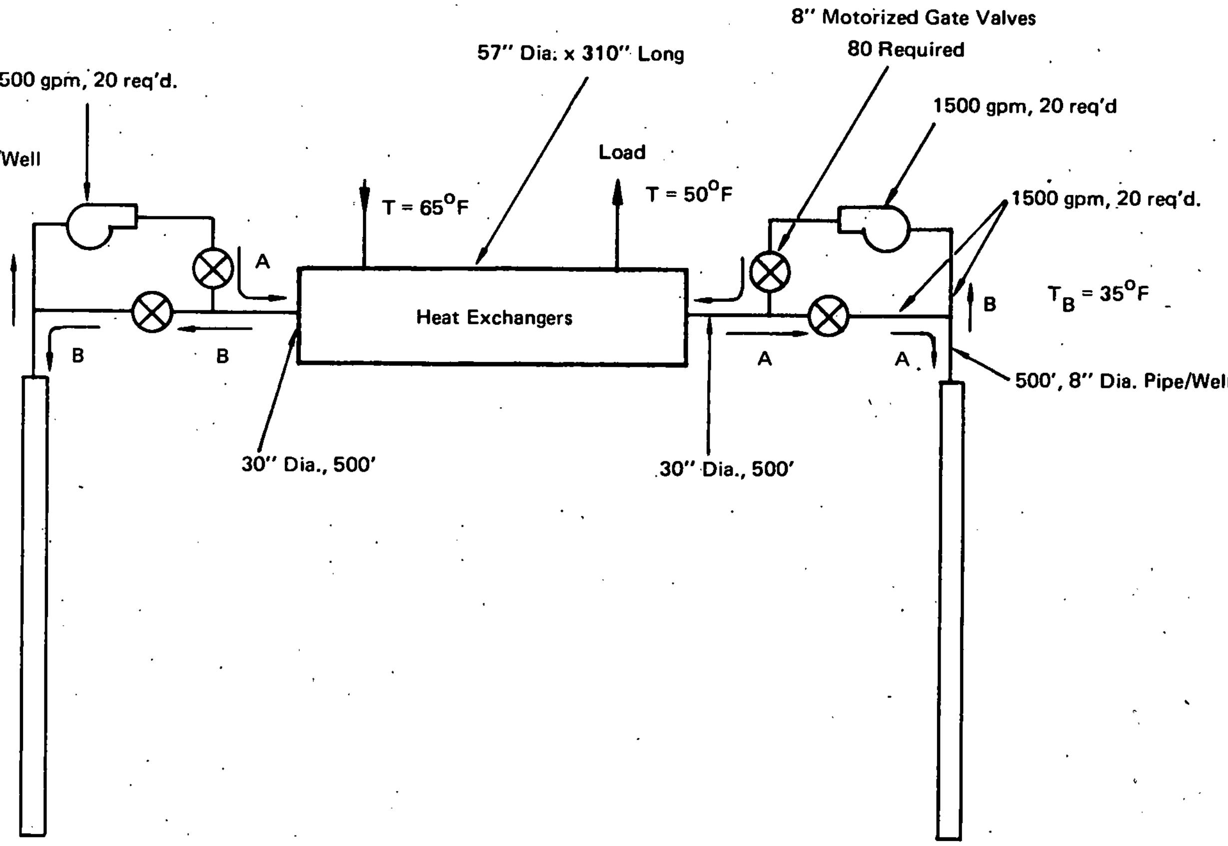
Figure 4-19 shows a system sized to meet the requirements of a terminal of JFK Airport. It utilizes a field of 40 wells to store chilled water to provide cooling during the summer time. In the winter time, the water is chilled utilizing either cool water from Jamaica Bay or water supplied from cooling towers already in place at the airport and pumped into 20 chilled water wells. During the summer, this chilled water is pumped through a heat exchanger to provide cooling to the building and then passed into another group of wells where it can be stored until it can be cooled again the following winter. Table 4-17 presents cost estimates for the system shown.

- Installation:

The major installation requirements for the system are the drilling of the 40 wells which are 36" in diameter and the installation of the piping connecting the well field with the cooling system of the building. This work is all done at the site including wiring of all controls using techniques that are standard for this type of fabrication.

- Operating Conditions:

This system as originally proposed utilized chilled water stored at 35°F to provide the cooling. Due to the requirements for a secondary heat exchanger between the well water and the cooling fluid in the air conditioning system, the delivered temperature of the cooling water to the air conditioning system will be 50°F, if a reasonably sized heat exchanger is used. Decreasing this temperature to the 45°F level with the secondary heat exchanger will add to the cost of the system, however, as indicated in earlier sections, 45°F is the maximum acceptable temperature for dehumidification of air according to standard HVAC system design practice. If the well water can be pumped directly to the air conditioning system, then there is no problem with the delivery rate capability of the system or the temperature of the cooling fluid.



- Warm Water Wells
- 20 Required
- 400 ft Deep

A: Charge
B: Discharge

- Community Sized System
- Storage Capacity: 200 x 10^9 Btu
- Discharge Rate: 288 x 10^6 Btu/hr

- Environmental Input Space Cooling (Seasonal)

FIGURE 4–19 DESERT RECLAMATION IND. (CONFIGURATION # 1) (CODE # 17)

TYPE: AQUIFER

CONTRACTOR: Desert Reclamation Industries (Code #17)

INPUT: Environmental

CYCLE: Seasonal

STORAGE CAPACITY: 200×10^9 Btu

DISCHARGE RATE: 288×10^6 Btu/hr Cooling

			(%)
STORAGE MEDIUM	A	$ -	-
CONTAINER	B	-	-
INSULATION	C	-	-
HEAT EXCHANGERS	D	350,000	8.2
FLUID	E	-	-
PIPING AND DUCTING	F	112,360	2.6
BLOWER & MOTOR	G	-	-
PUMP & MOTOR	H	359,600	8.4
CONTROLS	I	280,200	6.6
INSTALLATION COST	J	3,156,343	74.2
SYSTEM COST		4,258,503	100%
COST OF MAINTENANCE PER YEAR		75,000	
NO. OF SYSTEMS PER YEAR		1	

Table 4-17

COST SUMMARY - DESERT RECLAMATION INDUSTRIES (CONFIGURATION 1)

4.2.18 Texas A&M System

- Application:

The Texas A&M System is sized to provide cooling for a large apartment complex on a seasonal basis using environmental input.

- System Description:

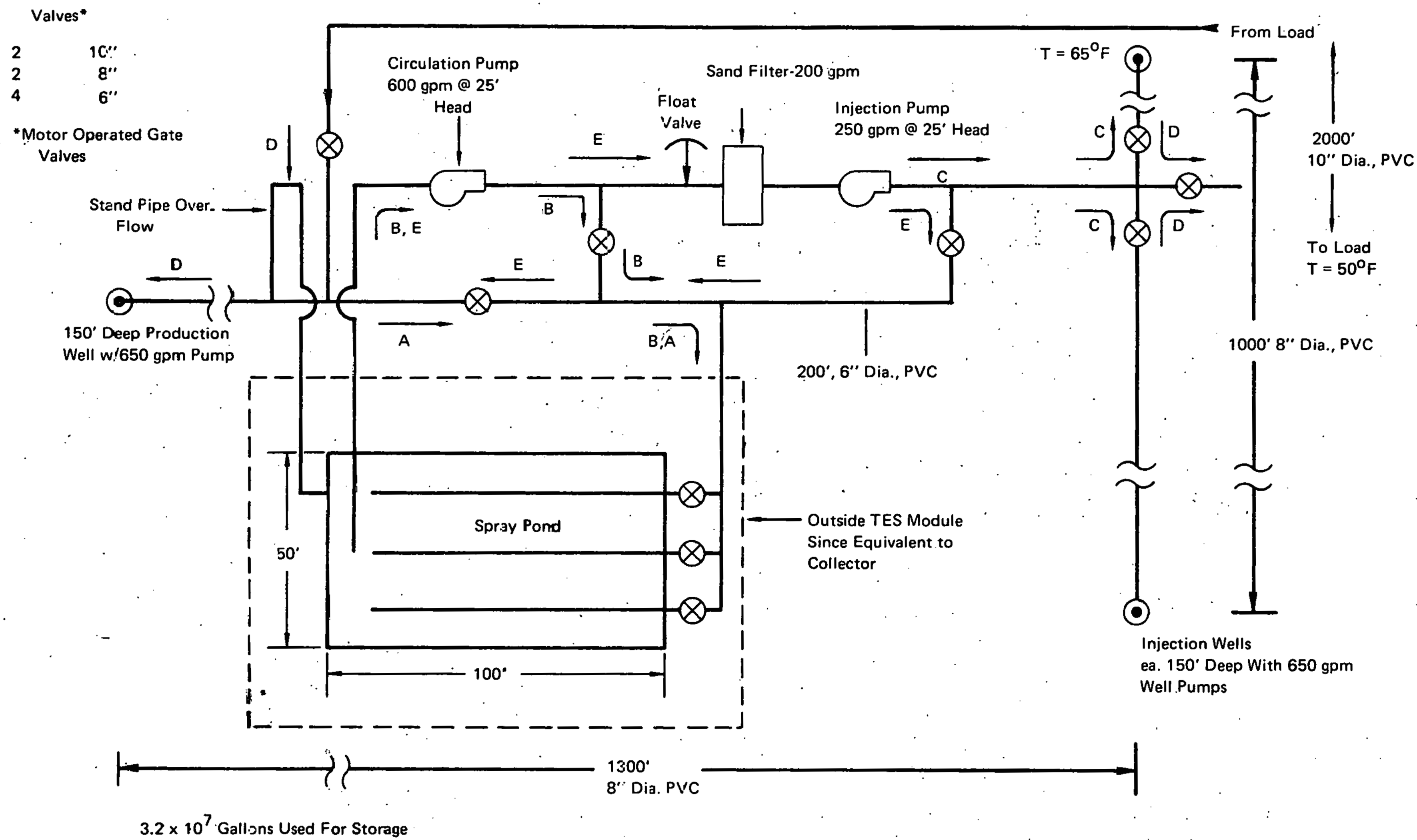
This system utilizes three wells (see Figure 4-20). Two wells store cool water and one well stores warm water after it has been used to cool buildings. Cooling of the water is done using a spray pond during the winter. Whenever ambient temperatures are such that water at a cool enough temperature can be produced, it is circulated through the spray pond from the warm water storage well, cooled at the spray pond, and then injected into the chilled water storage wells. During the summer time when cooling is required, water is pumped from the wells directly to the cooling system of the complex. Cost estimates for this system are given in Table 4-18.

- Installation:

The major installation requirements for the system are the drilling of the three wells and the installation of the piping required to connect the wells to each other and to the load. Standard installation techniques for this type of apparatus were used in costing the system.

- Operating Conditions:

The major limitation on this system is the ability to produce cool water in the winter time. The system presently being developed by Texas A&M is designed to provide 50°F water to the load. This is slightly warmer than normally acceptable in air conditioning applications. If the system were utilized in an area where the weather was cooler in the winter time, cooler water could be produced and the output temperatures from the well would be acceptable.



A – Filling Pond From Production Well
B – Chilling Water
C – Filling Injection Wells With Chilled Water
D – Chilled Water to Load
E – Pond to Production Well

- Large Apartment Building
- Storage Capacity: 4×10^9 Btu
- Discharge Rate: 10×10^6 Btu/hr
- Environmental Input, Space Cooling

FIGURE 4–20 TEXAS A&M (CODE # 18)

TYPE: AQUIFER

CONTRACTOR: Texas A&M University (Code #18)

INPUT: Environmental

CYCLE: Seasonal

STORAGE CAPACITY: $4X10^9$ Btu

DISCHARGE RATE: $10X10^6$ Btu/hr Cooling

			(%)
STORAGE MEDIUM	A	$ –	–
CONTAINER	B	–	–
INSULATION	C	–	–
HEAT EXCHANGERS	D	–	–
FLUID	E	–	–
PIPING AND DUCTING	F	22,363	17.6
BLOWER & MOTOR	G	–	–
PUMP & MOTOR	H	27,163	21.4
CONTROLS	I	11,291	8.9
INSTALLATION COST	J	66,139	52.1
SYSTEM COST		126,956	100%
COST OF MAINTENANCE PER YEAR		4,082	
NO. OF SYSTEMS PER YEAR		1	

Table 4-18

COST SUMMARY - TEXAS A&M UNIVERSITY

4.2.19 Desert Reclamation (Configuration 2)

- Application:

This DRI System was sized to provide cooling on a seasonal basis for a large apartment complex utilizing environmental inputs.

- System Description:

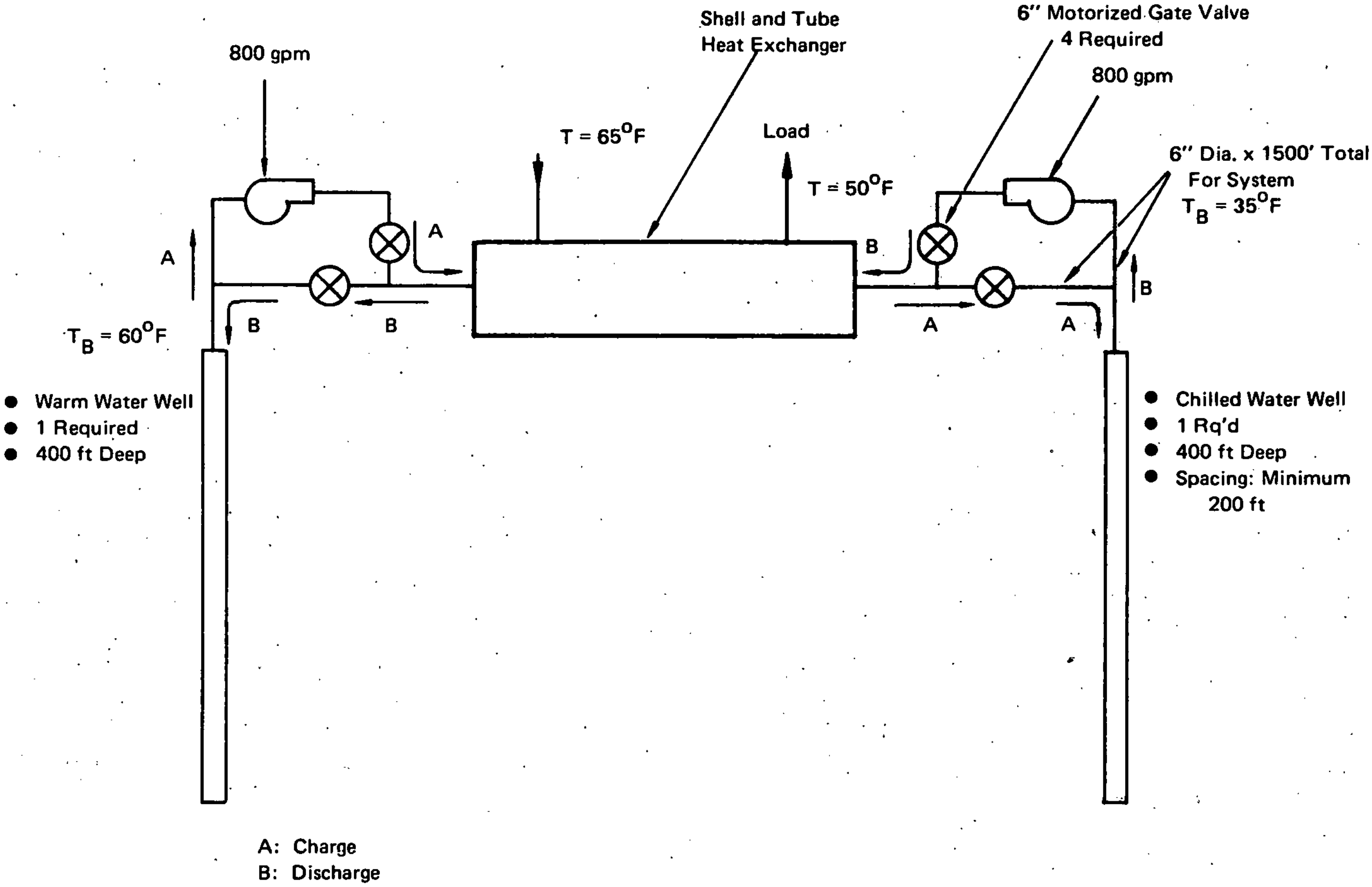
This system utilizes two wells (see Figure 4-21). Chilled water is supplied by an external source, either from a cooling tower or from a body of chilled cool water such as the ocean. As much cool water as possible is stored during the winter time. During the summer time, this chilled water is pumped through a heat exchanger and used to cool the load. The warmed water is stored in the second well until the following season when it is withdrawn and cooled whenever ambient conditions permit. Costs are estimated as shown in Table 4-19.

- Installation:

This system is installed using procedures similar to those described in Section 4.2.17.

- Operating Conditions:

The same considerations in the operation of this system apply as those described in Section 4.2.17.



- Large Apartment Building
- Storage Capacity: 4×10^9 Btu
- Discharge Rate: 10×10^6 Btu/hr
- Environmental Input
- Space Cooling (Seasonal)

FIGURE 4–21 DESERT RECLAMATION IND. (CONFIGURATION 2) (CODE # 19)

TYPE: AQUIFER

CONTRACTOR: Desert Reclamation Industries (Code #19)

INPUT: Environmental

CYCLE: Seasonal

STORAGE CAPACITY: $4X10^9$ Btu

DISCHARGE RATE: $10X10^6$ Btu/hr Cooling

		$	(%)
STORAGE MEDIUM	A	-	-
CONTAINER	B	-	-
INSULATION	C	-	-
HEAT EXCHANGERS	D	25000	10.7
FLUID	E	-	-
PIPING AND DUCTING	F	7665	3.3
BLOWER & MOTOR	G	-	-
PUMP & MOTOR	H	12680	5.4
CONTROLS	I	7440	3.2
INSTALLATION COST	J	180475	77.4
SYSTEM COST		233,260	100%
COST OF MAINTENANCE PER YEAR		3,265	
NO. OF SYSTEMS PER YEAR		1	

Table 4-19

COST SUMMARY - DESERT RECLAMATION INDUSTRIES (CONFIGURATION 2)

CHAPTER 5

BASELINE SYSTEMS

5.1 Introduction

In order to provide a basis for evaluating the different advanced TES systems, a baseline system has been identified for each of the applications described in Chapter 4. The baselines have been sized so that each baseline matches one or more of the applications for which the advanced technologies have been sized and costed. In this Chapter, these baseline systems are described in detail and cost estimates are summarized.

5.2.1 Passive Storage Systems (Code #B1)

Passive storage systems utilize a phase change material encapsulated in a standard building material such as a concrete block or ceiling tile. The baseline for this case is an equivalent building material without the PCM storage capability. In order to calculate the cost of adding the storage, the storage capacity of the PCM-impregnated building material is offset by the storage capacity of the building material without PCM and the cost of the block with storage capacity is offset by the cost of the material without storage capacity. This can then be used to calculate the cost of storage for a particular installation. Figure 5-1 shows the method applied to the Suntek and Brookhaven Systems as costed during this program. It should be noted that the costs used are the installed costs of the different systems.

Block With pcm

Block Without pcm

Cost = $\$_{pcm}$

Storage Capacity = Q_{pcm}

Cost = $\$_{B}$

Storage Capacity = Q_{B}

$$\text{Cost/Btu} = \frac{\$_{pcm} - \$_{B}}{Q_{pcm} - Q_{B}}$$

	Suntek[1]	Suntek[2]	Brookhaven[3]	Baseline
Price/Block (installed) ($)	9.86	4.53	7.05	1.72
Storage Capacity (Btu)	1450	1450	400	60[4]
Cost ($)/$10^6$ Btu offset by baseline	5860	2020	15,680	0

[1] Trombe wall with Beadwall insulation.

[2] Without insulation.

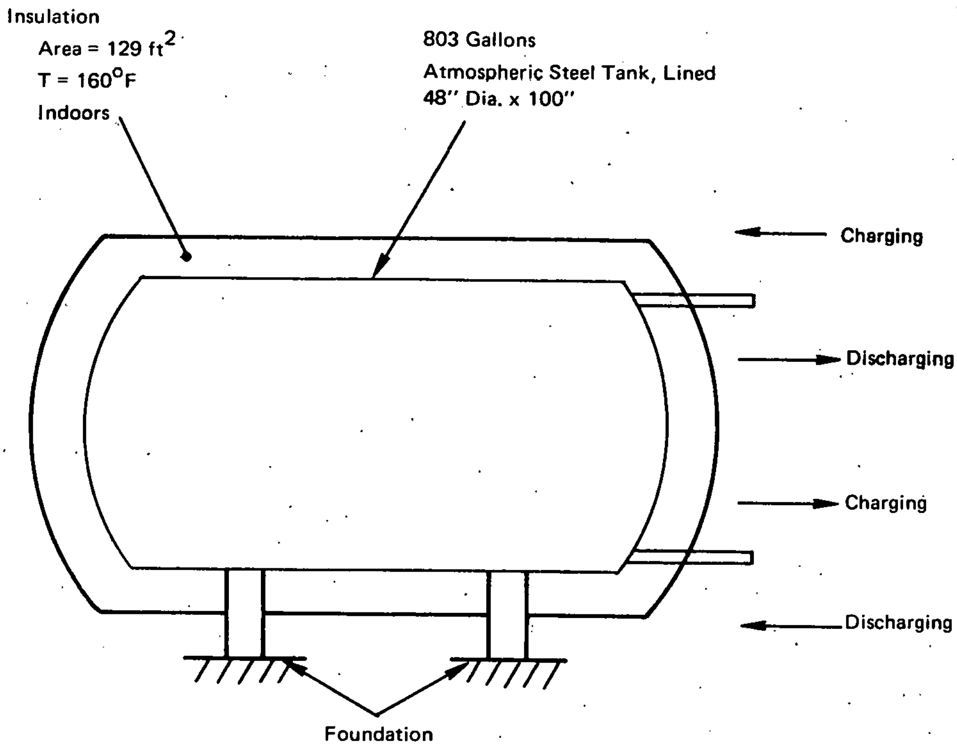
[3] Interior uninsulated wall.

[4] Based on 30 lb block cycling through 10°F differential.

FIGURE 5-1 PASSIVE SYSTEM BASELINE

5.2.2 Diurnal Solar Storage for Space Heating - Residential Installation with Hydronic System (Code #B2)

The system chosen as the baseline in this case, consists simply of a large steel tank containing hot water. This system, shown in Figure 5-2 for a 400,000-Btu capacity, consists of a 803-gallon tank lined with a coating to prevent corrosion. It contains water, which is cycled through a temperature range of 100°F to 160°F. The tank is insulated and covered with a sheet metal jacket. A cost estimate for this system is shown in Table 5-1.



- Residencc
- Storage Capacity, 400,000 Btu
- Discharge Rate, 50,000 Btu/hr
- Solar Hydronic Space Heating (Diurnal)

FIGURE 5–2 SOLAR HYDRONIC SPACE HEATING WITH DIURNAL STORAGE

		Item Cost ($)
STORAGE MEDIUM:	Water	0
CONTAINER:	• 803 gallon tank with supports and transportation	1,051
	• Lining 129 ft^2 @ \$2.50/ft^2	323
	• Jacket 129 ft^2 @ \$.37/ft^2	48
INSULATION:	129 ft^2 @ 160°F (\$.20/ft^2)	26
HEAT EXCHANGER:		0
HEAT TRANSFER SYSTEM:		0
CONTROLS:	1-Thermostat	35
TOTAL COMPONENT COST:		1,483
INSTALLATION:	• Labor - 8 hr @ \$20	160
	• Foundation	100
TOTAL		1,743

TABLE 5-1 HYDRONIC SOLAR SPACE HEATING BASELINE COSTS

5.2.3 Diurnal Solar Space Heating for Residences Using Hot Air (Code #B3)

The system chosen for this application is the Solaron rockbed heat storage system. Costs were derived based on design inputs from Solaron and quotes obtained from local vendors plus Means Data Book for 1978.*

The general design of the system costed is shown in Figure 5-3. This system is fabricated on site using readily available construction materials. The basic container is an 8" thick reinforced concrete wall. Near the bottom, forms are used to make air passages. Similar passages are made at the top of the container. The inside surfaces and the floor of the concrete container are lined with rigid fiberglass insulation. The insulation recommended is 5" thick for indoor applications, and 8" thick for outdoor applications. Sheet rock is placed over the bottom to distribute the load of the rock. 8" X 8" X 16" concrete beam blocks are spaced across the bottom of the container on top of the sheet rock. These blocks are "U" shaped and permit the air to circulate throughout the bottom of the container. Metal plaster lath is placed on top of the beam blocks to support the rock, which serves as the primary heat storage medium. The rocks are 1/2" to 1-1/2" pebbles, which can be purchased locally. The container is filled with this material to within a few inches of the top and is covered with a plywood and 2" X 4" panel, which contains fiberglass insulation. The lower portion of this cover is sheathed with sheet rock to insure that no materials that may give off resin come in contact with the air.

During use, cool air is always introduced at the bottom of the container and hot air at the top. Thus, during the charging cycle, hot air comes in at the top and cooler air is removed from the bottom. During discharge, cool air is introduced at the bottom and hot air removed at the top. According to the manufacturer, excellent stratification is obtained in the storage material in this fashion. The average temperature of the device is said to go from the top storage input temperature to ambient temperature during a normal use cycle. However, in practice, a somewhat smaller temperature differential is likely. Therefore, we have utilized a figure of 85°F to 140°F in calculating the storage capacity required. Based on the bulk density of this type of material, approximately 20 $Btu/°F \cdot ft^3$ can be obtained from this storage system.

Cost estimates were developed for three different system sizes. The system specifications are summarized in Table 5-2 and the costs are given in Table 5-3. Table 5-4 gives a detailed breakdown of the costs for one smaller system as an illustration of the costing procedure used. Using these figures, a curve which relates storage capacity to cost for rockbed storage systems was developed. This is shown in Figure 5-4. The cost ranges from $3.40 per cubic foot for a residential size system to $1.80 per cubic foot for a system sized for a large apartment. These are installed costs including normal overhead and profit which would be charged by a contractor to fabricate the device. This figure compares with a value of $3.00 to $4.00 per cubic foot given by the Solaron.

* Robert Snow Means Company, Inc., Building Construction Cost Data 1978. 36th Edition Duxbury, Mass., 1978.

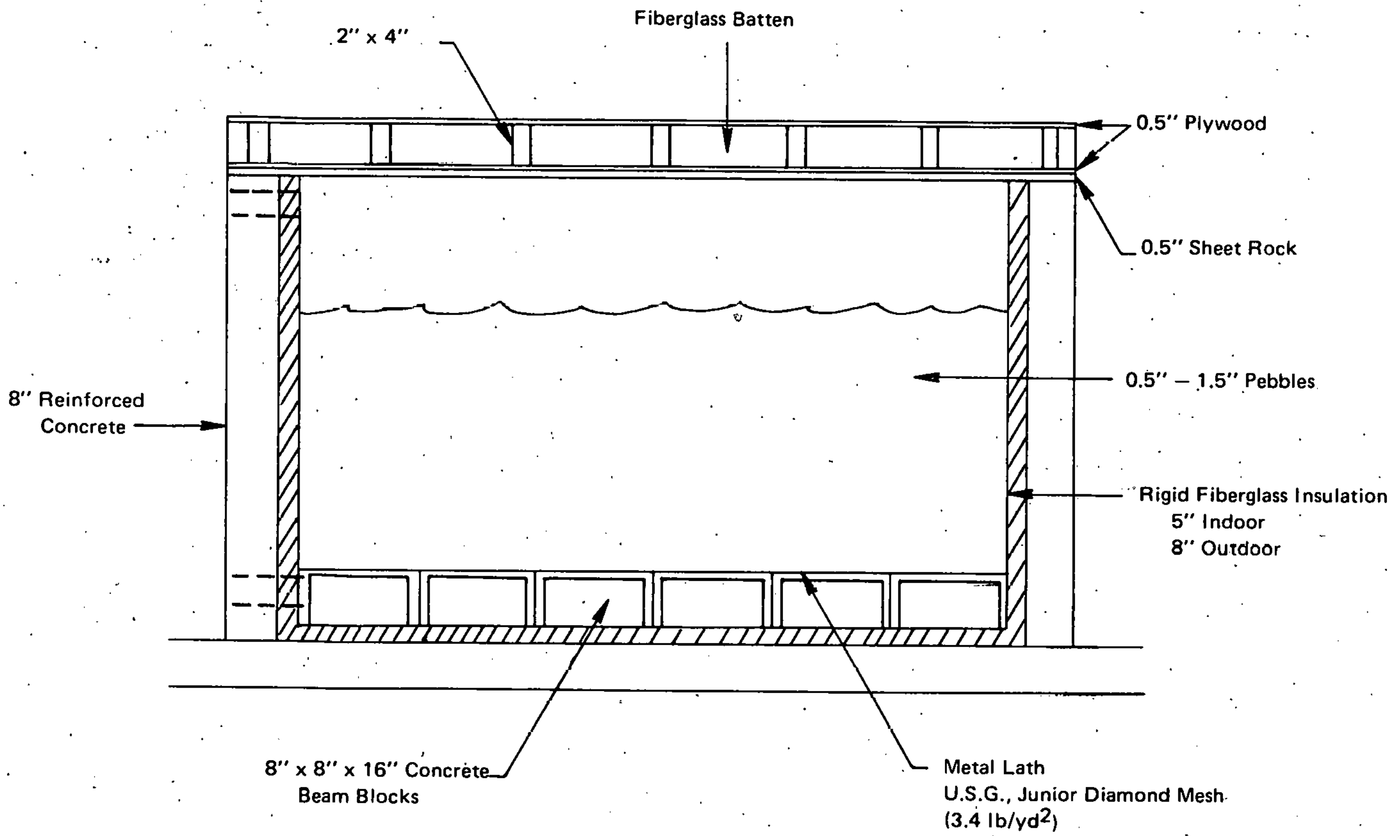


FIGURE 5–3 SOLARON ROCKBED STORAGE SYSTEM

STORAGE MEDIUM:	18 tons	45.5 tons	365 tons
CONTAINER:	7.2' X 10' X 5' high	13' X 14' X 5' high (includes cover supports)	30' X 49' X 5' (includes cover supports)
COVER:			
• Plywood (ft^2)	144	364	2940
• Sheet rock (ft^2)	72	182	1470
• 2" X 4" (ft)	50	100	800
• Metal lath (ft^2)	72	182	1470
• Bond beam blocks	60	150	1180
INSULATION:			
• 5" urethane (ft^2)	244	452	2260
• 3-1/2" fiberglass (ft^2)	72	182	1470

NOTE: Fabrication and installation labor included in costs.

TABLE 5-2 ROCKBED STORAGE SYSTEM GENERAL SPECIFICATIONS

	Cost ($) for System Size Indicated		
Element	400,000 Btu	1×10^6 Btu	8×10^6 Btu
Storage Medium	90	228	1,825
Container	692	1,340	5,935
Cover	116	245	2,017
Insulation	335	633	3,306
Controls	35	70	140
TOTAL	1,268	2,516	13,223

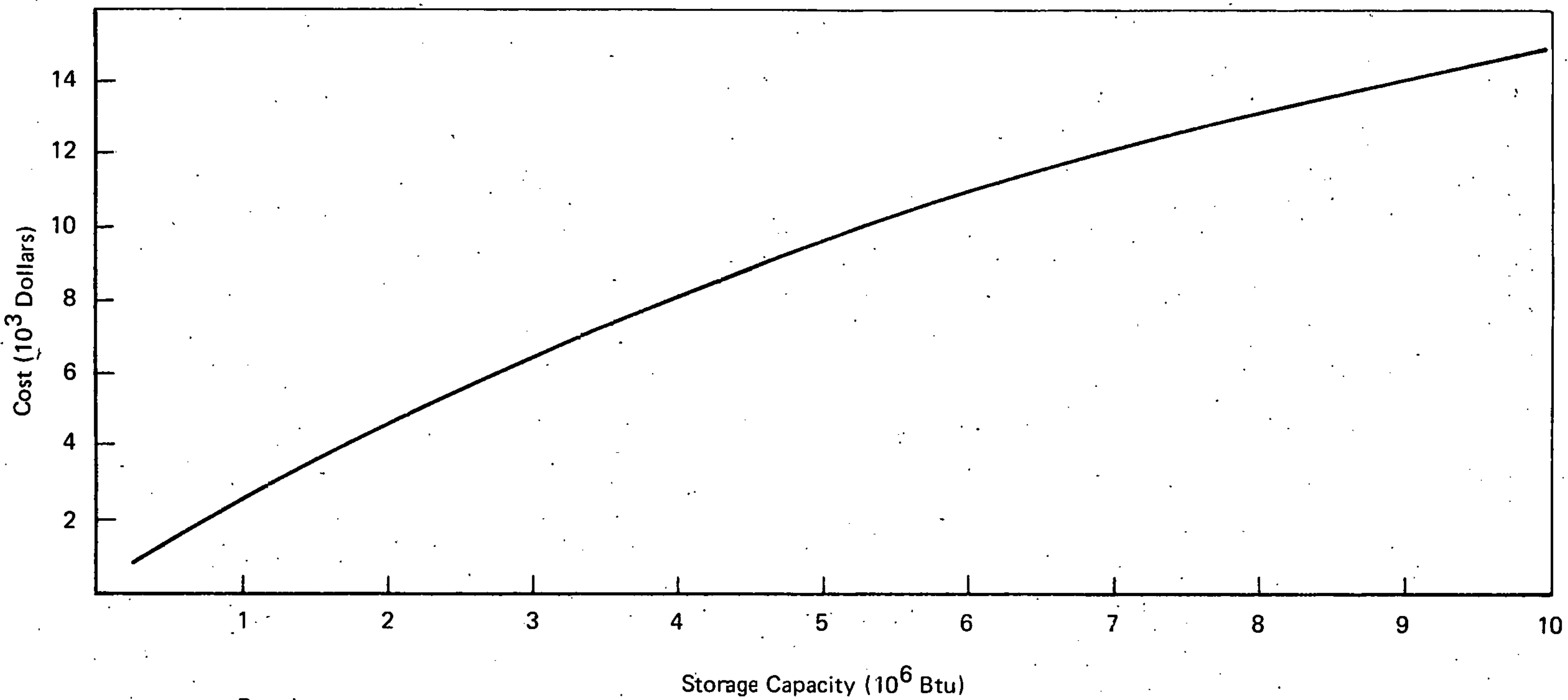
TABLE 5-3 COSTS OF SOLARON ROCKBED STORAGE SYSTEM

TABLE 5-4

400,000 BTU ROCKBED STORAGE COST DETAILS

		Cost* ($) Breakdown	Total ($) for Element
Storage Medium:	18 tons @ $5.00/ton		90
Container:	7.2' x 10' x 5' high, 8" reinforced concrete. Assumed cost of two walls partially offset by cost of concrete block wall and 4" of additional concrete required for floor.		555
	Top (excluding insulation):		
	plywood 6 sheets 4'x8' @ $11.50 ea	69	
	Sheet rock 3 sheets 4'x8' @ $352 ea	11	
	2"x4" 50'*@ $.22/ft	11	
	Labor $.35/ft.^{2}	25	116
	Bond Beam Blocks 60 @ $.66 ea.		40
	Metal Lath 3.4 lb/yds (black) (installed)		24
	Sheet rock: 3 sheets 4'x8' @ $3.52 ea		11
Insulation:	Sides and Bottom, 244 ft.^{2} @ $1.30/ft.^{2} installed	327	
	top, 72 ft.^{2} @ $.25/ft.^{2}	18	335
Controls:	1-Thermostat		35
Installation:	Installation of Blocks & Gravel ** 1 driver with truck plus 2 laborers 1 hr. @ $62/hr.		62
Total Cost			1268

* All labor includes overhead & profit, materials are delivered prices.
** Assumes crew on site for other work.



Based on:

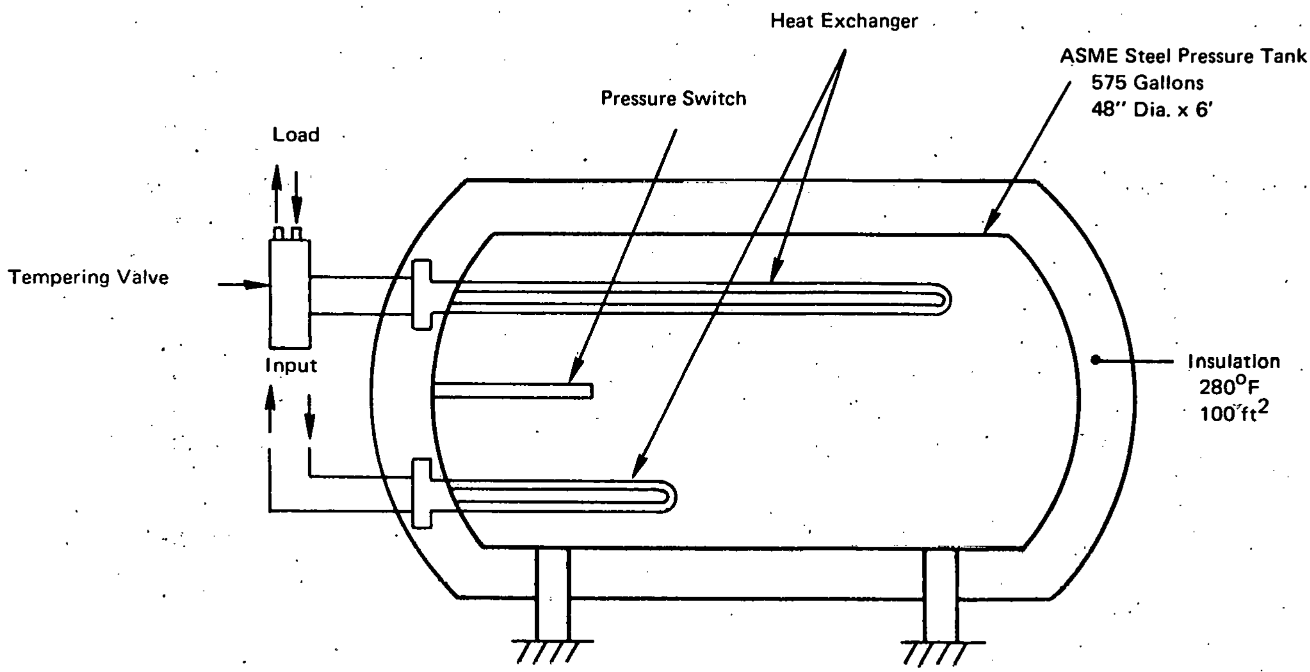
- 1100 Btu/ft^3
- Temperature range: 85°F–140°F

FIGURE 5–4 ROCKBED STORAGE COSTS

5.2.4 Pressurized Hot Water Storage for Solar Space Cooling (Code #B4)

The Megatherm pressurized hot water storage system was selected as the baseline storage system for applications utilizing stored solar energy to run absorption air conditioners for space cooling. The Megatherm system as shown in Figure 5-5 consists of a large steel tank equipped with two heat exchangers. The heat exchanger positioned near the bottom of the tank inputs energy from the solar collector. The temperature on the input side is 300^{o}F. The top heat exchanger inputs energy to the absorption air conditioner as required at a temperature of 200^{o}F. The output heat exchanger is equipped with a tempering valve,which mixes outgoing hot water with incoming cool water to maintain a constant temperature on the outlet side. This system is suitably insulated for temperatures of this size and is surrounded by a sheet metal enclosure. Control of the input is done by a pressure switch,which mechanically senses the pressure in the tank and shuts off the input when the temperature as indicated by the pressure switch reaches a predetermined level.

Cost estimates were obtained from Megatherm for three different system sizes. The system shown in Figure 5-5 is sized for a residential cooling application. Two other systems: one sized for a small apartment building and the other sized for a large apartment building were also costed. The specifications and costs for these systems are shown in Table 5-5. A graph relating the cost of this solar energy storage system utilizing pressurized hot water versus capacity is shown in Figure 5-6.



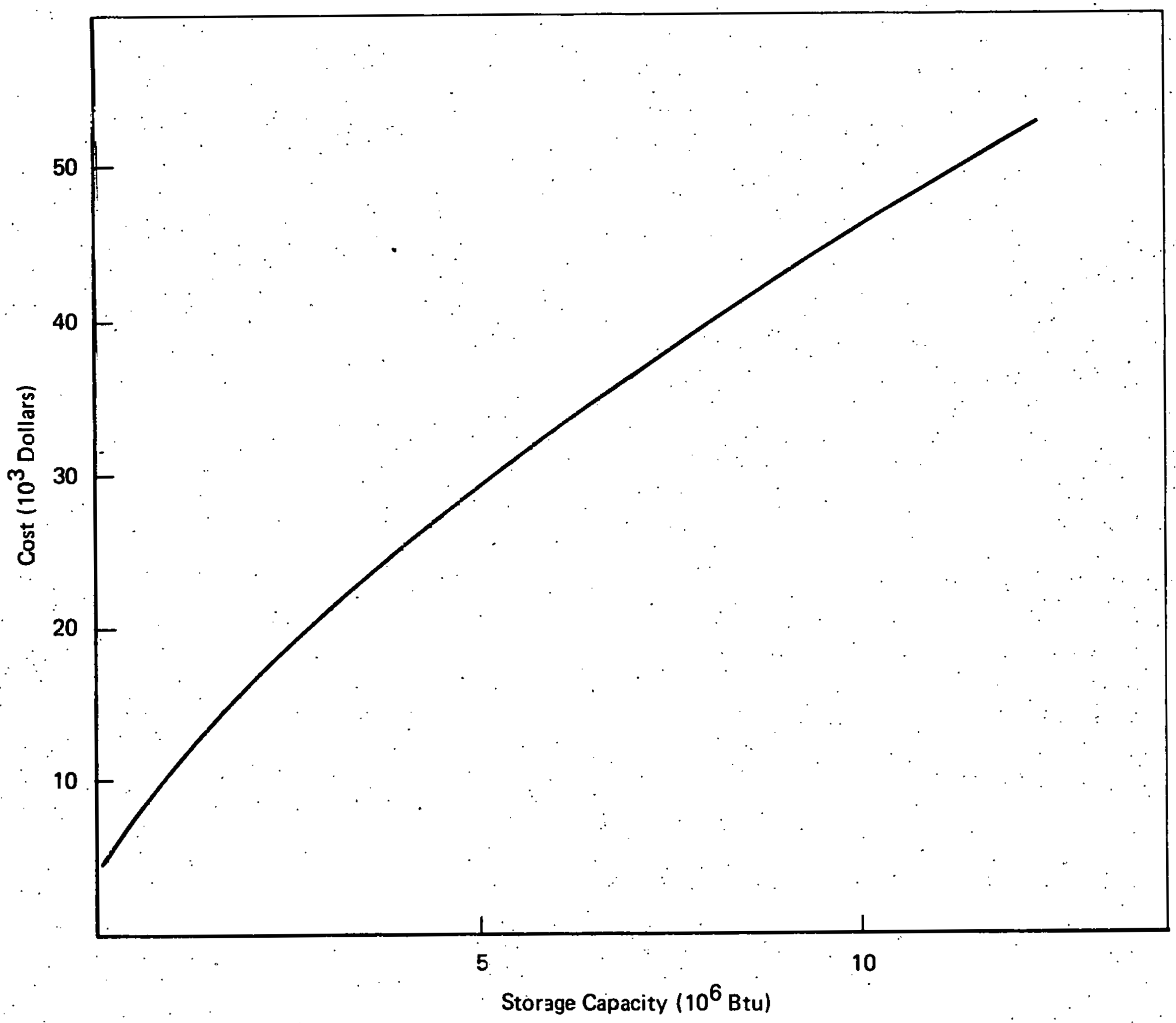
- Residence
- Storage Capacity: 250,000 Btu
- Discharge Rate: 50,000 Btu/hr
- Solar Space Cooling (Diurnal)

FIGURE 5–5 BASELINE SOLAR COOLING

Size (Gallons)	Storage Capacity (Btu)	Input/Output Rate (Btu/hr)	Input/Output Temperature (°F)	Cost	$\$/10^6$ Btu
575	250,000	50,000	300/200	5,400	21,600
2,233	1×10^6	200,000	300/200	10,900	10,900
Two Tanks @ 12,465 each	12×10^6	2.4×10^6	300/200	52,000	4,300

TABLE 5-5 MEGATHERM COSTS FOR PRESSURIZED HOT WATER STORAGE FOR SOLAR SPACE COOLING

NOTE: Add 10% to cost shown to allow for transportation and installation.



Note: Add 10% to cost shown to allow for transportation and installation.

FIGURE 5–6 COST OF MEGATHERM SYSTEM VS SIZE FOR USE WITH SOLAR INPUTS FOR ABSORPTION AIR–CONDITIONING

5.2.5 Solar Heating and Cooling System for Diurnal and Seasonal Storage Applications (Code #B5)

The system used as the baseline for this application is shown schematically in Figure 5-7. The basic storage element is a large tank containing water. The type of tank chosen and the place where it is installed, depend on the type of application. The following tank types and locations were used in this study:

- residential diurnal - unpressurized stell tank located indoors;
- commercial diurnal - unpressurized steel tank located outdoors;
- residential season - unpressurized steel tank buried;
- commercial seasonal - prestressed concrete tank located above ground.

For the seasonal storage application, a cylindrical polyethylene liner was used to separate the hot storage for solar air conditioning from the warm storage used for space heating and water heating. This would be fabricated as a large cylinder, which could be suspended from the inner walls of the outer container. It was assumed that this separator would be partially fabricated in a factory from 5-foot wide, continuously extruded polyethylene sheets. Final assembly at the site would involve snapping together the final seam to make a cylinder and suspending it from the walls of the outer tank.

For the diurnal storage application, the tank was sized based on the requirement for cooling, using 25° temperature differential from 205° to 180°F. For the seasonal storage case, the model described in Chapter 6 was used to estimate the amount of storage required. In this case the inner container was assumed to cycle between 180° and 200°F and the outer container from 200°F to ambient temperature. The tank is insulated in the seasonal case to achieve an average standby loss of less than 2 Btu/hr/ft^2 using 5 inches of polyurethane foam. In the diurnal storage case, standard fiberglass insulation was used. For outdoor installations a waterproof cementitious coating was assumed.

The hot water supplied by the storage system is used either to provide space and water heating directly, or to drive an Arkla absorption air conditioner. Cooling was provided to the Arkla unit by a conventional cooling tower.

The system configured in this way provides performance equivalent to that of the chemical heat pump systems analyzed in earlier sections. The details of the elements chosen for estimating the cost of specific systems, which can be compared directly with chemical heat pump systems, are shown in Tables 5-6 through 5-11.

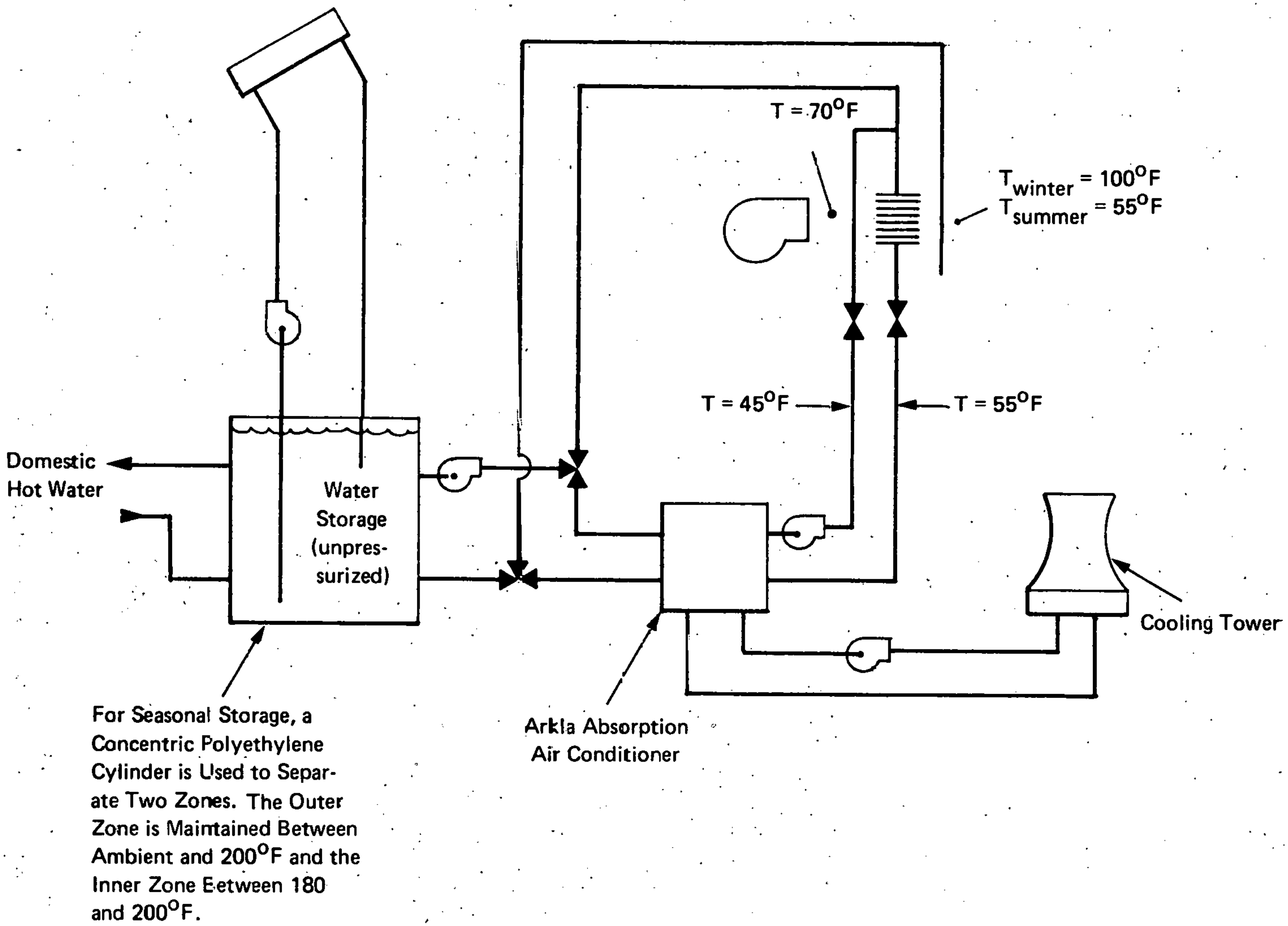


FIGURE 5–7 BASELINE SYSTEM FOR COMPARISON WITH CHEMICAL HEAT PUMPS

		Cost ($)
Storage Medium:	Water	0
Container	• 1660-gallon steel tank, unpressurized	1340
	• Temperature differentials - summer: 205-180°F* - winter: 130-100°F	
	• Installed indoors	
	• Lining 207 ft^2 at $2.50/$ft^2$	570
	• Jacket 207 ft^2 at $10.37/$ft^2$	80
Insulation	207 ft^2 at $0.27/$ft^2$	60
Installation	• Foundation	200
	• Labor 2 men/crane 4 hours at $100/hr	400
	Subtotal	2,600
Residential HVAC System Cost		10,160
	Total	12,760

*Used for sizing tank.

TABLE 5-6 RESIDENTIAL SIZED DIURNAL SOLAR SPACE HEATING AND COOLING - BASELINE COSTS

Tanks	- 2 tanks installed outdoors		
	- Temperature differentials*		
	• summer - 205-180°F**		
	• winter - 130-100°F		
	- Capacity 16,700 gallons each		
	- Cost (total)		
	• Tanks (steel, unpressurized)		12,970
	• Insulation at $1.85/ft^2$		3,840
	• ZRC coating at $2.50/ft^2$		5,180
	• Installation		4,000
		Subtotal	25,990
Commercial HVAC System Costs			51,590
		Total	$77,580

*These are working tank temperature differentials. Assuming a well stratified storage tank and temperature drops of 30°F through the heating system and 25°F through the chiller, inlet temperatures to the collector will average below 100°F in the winter and 200°F in the summer.

**Summer differential used for sizing tank.

TABLE 5-7 COMMERCIAL SIZE DIURNAL SOLAR SPACE HEATING AND COOLING - BASELINE COSTS

Storage Container

Tank (36,900 gallons)	13,400
• Unpressurized steel	
• Buried	
Tank Installation	3,000
Polyethylene Separation Sleeve	
• Material 650 ft^2 x 1/8" at $1/lb	430
• Factory assembly	250
• Transportation	50
• Site erection	140
Insulation (1595 ft^2)	5,700
• 5 inch urethane	
• Cementitious coating	
• $3.56/$ft^2$	
ZRC Coating (Rust Proof)	3,330
• 1330 ft^2 at $2.50/$ft^2$	
Subtotal	26,300
Residential Sized HVAC System (Arkla)	10,200
• 3 tons cooling plus cooling tower	
• Pumps, blower, heat exchanger piping, controls, and installation	
Total	$36,500

TABLE 5-8 RESIDENTIAL SIZE SEASONAL STORAGE SOLAR SPACE HEATING AND COOLING – BASELINE SYSTEM COST

Storage Container

Tank (342,000 gallons)	145,000
• Prestressed concrete	
• Installed	
Polyethylene Separation Sleeve	
• Material: 2400 ft^2 x 1/8" at \$1/lb	1,600
• Factory assembly	500
• Transportation	200
• Site Erection (crane plus crew)	1,000
Insulation (5831 ft^2)	21,300
• 5 inch urethane	
• Cementitious coating	
• \$3.56/ft^2	
Waterproofing at \$0.57/ft^2	3,400
Subtotal	173,000
Commercial Sized HVAC System (Arkla)	51,600
• 50 tons cooling plus cooling tower	
• Pumps, blower, heat exchanger, piping controls, and installation	
Total	224,600

TABLE 5-9 COMMERCIAL SIZE SEASONAL STORAGE SOLAR SPACE HEATING AND COOLING - BASELINE SYSTEM COST

Arkla Absorption Cooler Model WF36	3,300
Cooling Tower (10 ton)	1,250
Heat Exchangers 350 ft^2 (finned tube)	365
Piping	204
Blower (2 speed: 2212 - 1536 CFM)	952
Pumps (3) 11, 12, and 7.2 gpm	874
Controls	1,060
Installation	2,151
	10,156

TABLE 5-10 BASELINE COSTS FOR RESIDENTIAL SOLAR HVAC SYSTEM

Commercial HVAC System Costs

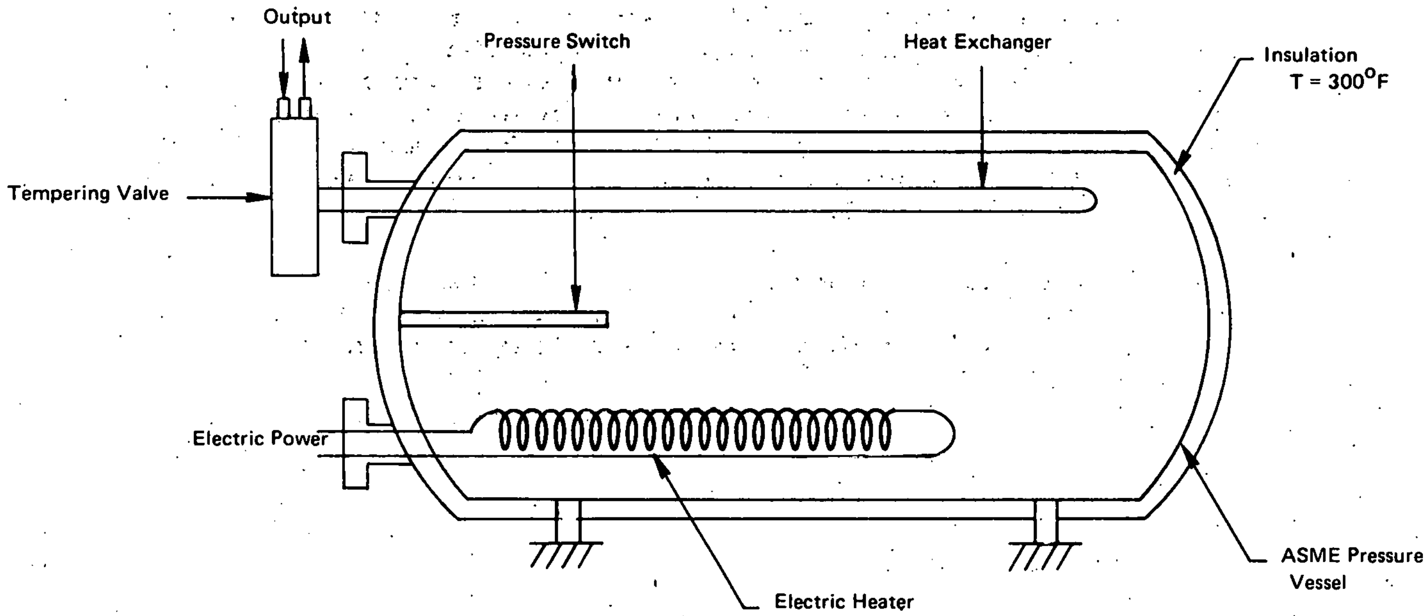
Arkla Absorption Cooler (25 ton units)		$29,400
Cooling Tower		5,000
Heat Exchangers 6767 ft^2, finned tube		3,340
Piping		1,350
Blower 2 speed (36,870 - 30,720 cfm)		3,520
Pumps	2 at 180 gmp $1168 1 at 120 gmp $480	1,650
Controls		1,580
Installation		5,750
		51,590

TABLE 5-11 BASELINE COSTS FOR COMMERCIAL SOLAR HVAC SYSTEM

5.2.6 <u>Storage of Off-peak Electric Energy for Hydronic Space Heating</u> (Code #B6)

A pressurized water system was chosen as the baseline for this case. A typical unit is shown in Figure 5-8. This unit is based on Megatherm storage heaters. It uses an electric heater positioned near the bottom of the tank to charge the system and a water-to-water heat exchanger near the top of the tank to extract energy. The extraction side is fitted with a tempering valve to maintain a uniform outlet temperature. The temperature from the system is regulated to provide water at a minimum value of 100°F. The temperature in the tank reaches a maximum of 280°F and is controlled with a pressure switch, which is adjusted so that it shuts the system off at 280°F.

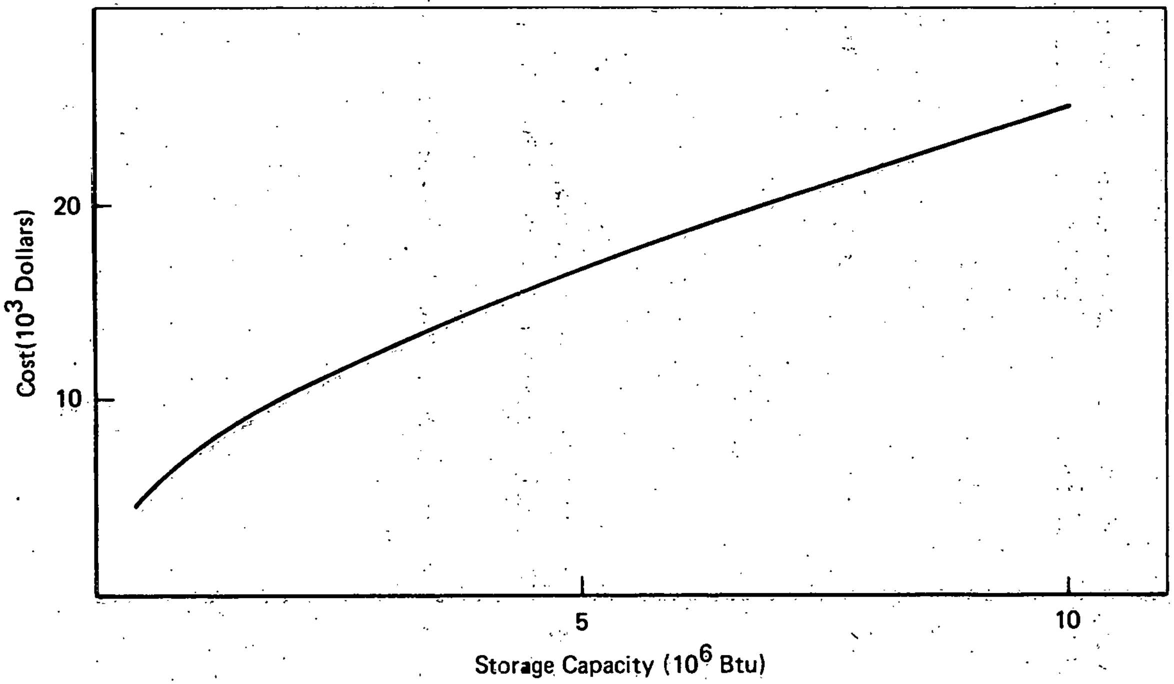
Cost estimates obtained from Megatherm for this system are shown in Table 5-12. A range of values was costed and, using the data provided, a curve relating cost to size was developed. This is shown in Figure 5-9.



Assumptions

- Temperature Range: 280 – 120°F
- Minimum Temperature Difference Across Heat Exchanger is 20°F
- Minimum Output Temperature is 100°F

FIGURE 5–8 MEGATHERM OFF-PEAK ELECTRIC SPACE HEATER FOR HYDRONIC APPLICATIONS



Note: Add 10% to cost shown to allow for transportation and installation.

FIGURE 5–9 COST OF MEGATHERM OFFPEAK STORAGE SYSTEM VS. SIZE FOR HYDRONIC SPACE HEATING

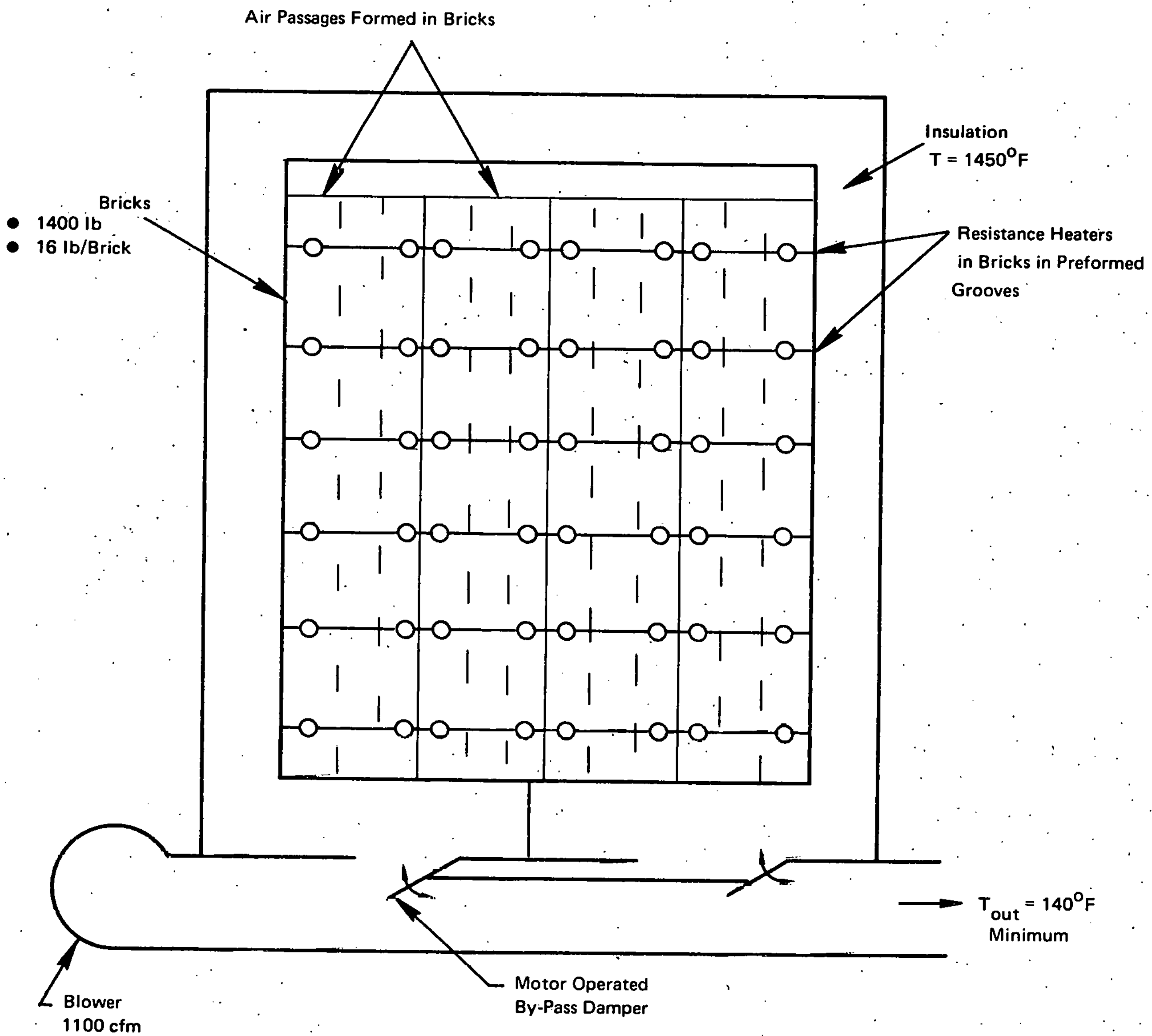
Size (Gallons)	Storage Capacity (Btu)	Input Rate (kw)	Output Rate (Btu/hr)	Minimum Output Temperature °F	Cost ($)
363	400,000	17	50,000	100	5,000
853	1×10^6	43	1.25×10^5	100	7,400
6,764	8×10^6	320	1×10^6	100	22,000

TABLE 5-12 COST OF PRESSURIZED WATER STORAGE FOR OFF-PEAK ELECTRIC HEATING USING HYDRONIC SYSTEM (MEGATHERM)

NOTE: Add 10% to cost shown to allow for transportation and installation.

5.2.7 Off-peak Storage of Electricity for Forced Air Space Heating (Code #B7)

The baseline system used in this case is based on the units sold by TPI Corporation. This unit is a modification of the Creda unit which is manufactured in England. A schematic showing the important features of this sytem is shown in Figure 5-10. The system utilizes ceramic bricks cast in a special shape that makes air passages and provides holes for heating elements and temperature controllers when the bricks are stacked up. For a storage capacity of 400,000 Btu's, approximately 1400 pounds of bricks are required. These bricks are cycled through a temperature range of approximately 200°F to 1380°F. The system is equipped with a double motor-operated bypass damper, which in initial operation is set so that the air blown through the unit passes straight through without going through the hot bricks. A temperature controller on the outlet side senses the air temperature and slowly opens the bypass damper letting a small amount of air pass through the bricks. This air then rejoins the main air stream and heats it to the desired outlet temperature of 140°F. As the unit is discharged, the bypass dampers open more and more, passing more air through the bricks and less through the straight paths. This varying air path provides a constant outlet temperature. Also shown in the figure is a estimate of the installed cost of a system based on the price to the installer quoted by TPI.



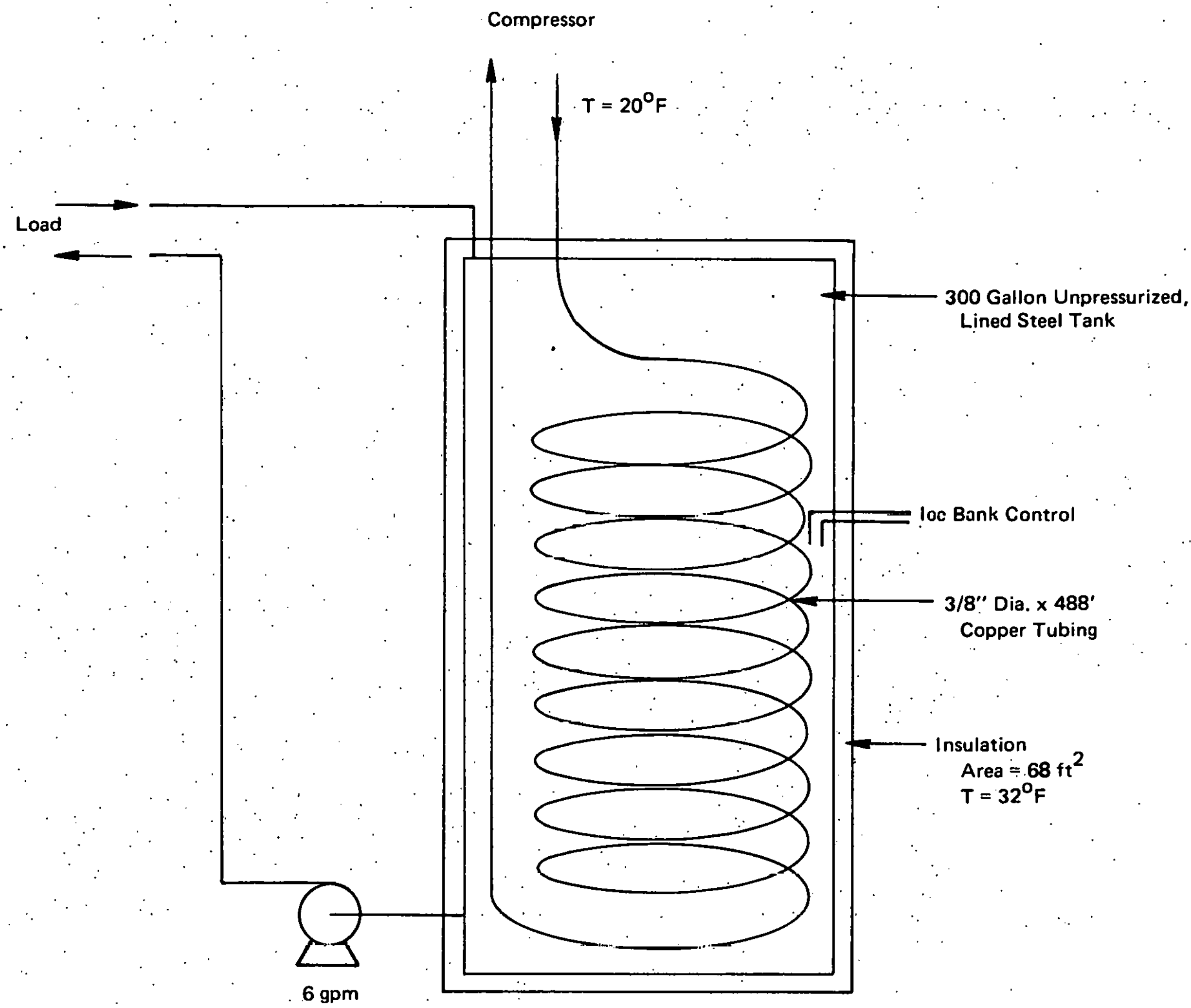
- Residence
- Storage Capacity: 400,000 Btu
- Discharge Rate: 85,000 Btu/hr
- Off-Peak Electric Heating (Diurnal)
- Cost:

To Installer	$800
To Customer	$960
Installation (4 hr @ $20/hr)	$ 80
Shipping	$ 50
Total	$1090

FIGURE 5–10 REPRESENTATIVE CERAMIC BRICK HEAT STORAGE UNIT FOR OFF-PEAK RESIDENTIAL SPACE HEATING

5.2.8 Off-peak Coolness Storage Using Ice for Residential Space Cooling (Code #B8)

The system picked as the baseline is based on a unit currently being developed by A. O. Smith Corporation. This unit, shown schematically in Figure 5-11, utilizes a standard unpressurized lined steel tank containing a large copper coil, which is connected to the air conditioning compressor. In order to charge this sytem, the coil is used as an evaporator and the compressor runs to build up ice on the coil. An ice bank control made by Ranco senses the thickness of the ice and shuts off the system when the unit is fully charged. In the fully charged state, there is still a certain percentage of water surrounding the ice. In order to discharge this system, a circulating pump takes the chilled water which is in contact with the ice and circulates it through a coil mounted in the cooling duct. This provides a constant 32°F temperature to the air conditioning duct. Cost estimates for this system are given in Table 5-13.



- Residence
- Storage Capacity: 250,000 Btu
- Delivery Rate: 35,000 Btu/hr
- Off-Peak Electric Cooling (Diurnal)

FIGURE 5–11 RESIDENTIAL-SIZED OFF-PEAK SPACE COOLING STORAGE USING ICE

TABLE 5-13

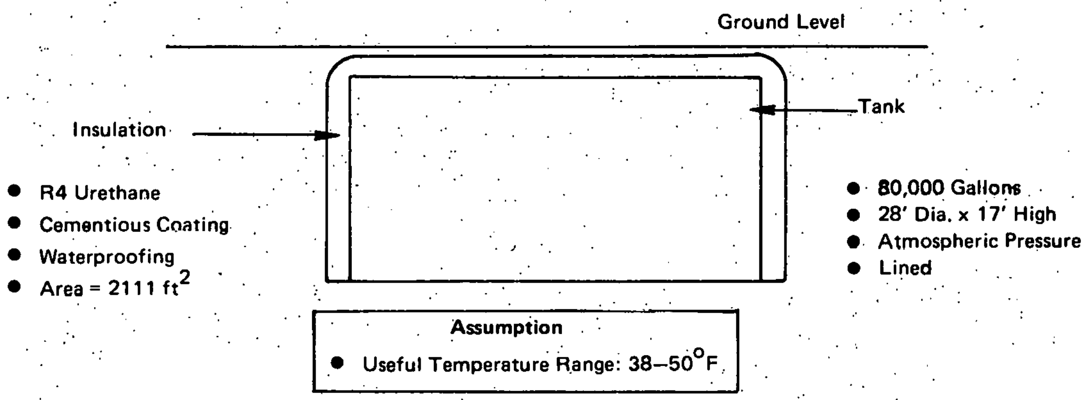
COST OF RESIDENTIAL SIZED OFF-PEAK COOLNESS STORAGE USING ICE

	COST $
Storage Medium	
(Ice)	0
Container	
300 gallon lined tank unpressurized	880
jacket 68 ft^2 @ $.37/$ft^2$	25
Insulation	
68 ft^2 @ .12/ft^2	8
Heat Exchanger	
Materials 3/8" tubing X 488' copper @ $.14/ft	68
Labor .5 hr @ $30/hr	15
Piping 10'X1/2" copper @ $.42/ft	4
Circulating Pump 6 gpm	70
Control	
Ice Bank Control	20
Total (Components)	1090
Installation 3 hrs. @ $20	
Shipping .05% of materials	55
Total	1205

5.2.9 Off-peak Electric Coolness Storage Using Chilled Water for Small Apartment Buildings (Code #B9)

The system chosen in this case utilizes a buried tank to store chilled water for space cooling (Figure 5-12). The tank was sized assuming that the water could usefully cycle through a temperature range of 38-50°. Since this was a diurnal application, an insulation with a R factor of 4 was used. This insulation was assumed to be coated with a cementitious covering and water proofed. 80,000 gallons are required for this application. The tank is quite similar to that used for space heating using seasonal hydronic storage except that the insulation value is smaller due to the diurnal application. Cost estimates for the installed tanks are given in Table 5-14.

During this analysis, a comparison was made between using chilled water storage and ice storage for larger applications because the size of the ice tank required would be significantly smaller than that required for chilled water. The calculations indicated that a tank size of 10,000 gallons would be adequate for ice storage based on a storage capacity of 6,000 Btu/cubic foot of storage capacity, while 80,000 gallons would be required using chilled water. The installed cost of the storage modules for the two systems differs by a factor of six, with the chilled water system costing approximately $42,000 and the ice system, also based on a buried tank, costing approximately $8,000. However, data on the cost of the compressors and ice-making heat pump required to charge these systems at a charging rate of 750,000 Btu/hr indicated that the chilled water equipment was much less expensive than the ice-making equipment. Data from Turbo Refrigeration for an ice-making unit sized to this specification gave a cost of $55,000 for the cooling equipment, while a Carrier quote for the same size installation based upon chilled water indicated an equipment cost of $16,000. Thus, the total installed cost for the chilled water system ($58,000) would be slightly less than that for the ice-making system. It is possible for larger installations that this trend would be reversed ($63,000). In addition, the ice-making equipment is still in the developmental stages, whereas the standard chilled-water compressors have been used for a long time. Therefore, it is possible that the slight cost advantage of the chilled water system will be lost in the future.



- Small Apartment Building
- Storage Capacity: 8×10^6 Btu
- Discharge Rate: 1×10^6 Btu/hr
- Off-Peak Cooling (Diurnal)

FIGURE 5–12 OFF-PEAK CHILLED WATER COOLING STORAGE FOR SMALL APARTMENT BUILDINGS USING A BURIED TANK

	Cost ($)
CONTAINER:	
• Steel unpressurized tank	28,100
• 17 ft high X 28 ft diameter	
• 80,000 gallons	
• Lining @ \$2.50/ft for 2,111 ft^2	5,280
INSULATION:	
• Urethane R=4	
• Cementitious coating	
• Waterproofing	
• Sides and top 2,111 ft^2 @ \$1.67	3,530
INSTALLATION:	5,100
• Including excavation and back filling assuming no blasting necessary	
TOTAL:	42,010

TABLE 5-14 COST OF DIURNAL COOLNESS STORAGE FOR OFF-PEAK ELECTRICITY FOR SMALL APARTMENT BUILDINGS USING CHILLED WATER

CHAPTER 6

EFFECTS OF STORAGE TEMPERATURES ON HARDWARE AND OPERATING COSTS OF ELEMENTS OUTSIDE THERMAL STORAGE MODULE

6.1 Introduction

The primary analysis done during this program has concentrated on the cost of the thermal energy storage module itself. Actually, however, some hardware costs and operating costs are affected by characteristics of the thermal energy storage system. Three specific cases are treated in this study:

- Effect of high storage temperatures on collector cost: For solar systems the storage temperature affects the cost of the collectors required due to the reduced solar collector efficiency translates to a requirement for a larger solar collector area and higher priced collectors. This is a hardware cost. It does not relate to operating characteristics of the system once the initial hardware has been purchased.

- Effect of low storage temperatures on compressor costs: Low temperature storage devices for storing coolness using off-peak electricity cost more to operate when the storage temperature is lower due to the reduced air conditioner efficiency.

- Effect of chemical heat pump C.O.P. and collector temperature on storage size and collector area.

In this chapter the first two areas are considered and an analysis presented for evaluating the effect of these differences on the cost of the total storage system including input and output characteristics. Chapter 7 deals specifically with the third area for chemical heat pumps.

6.2 Effect of Solar Temperature on Solar Collector Costs

In order to estimate the solar collector costs for storage temperatures, we first developed a relationship between the collector cost per million/Btu's per year collected versus storage temperature averaged in such a way as to provide an estimate of the cost differential for an average U.S. installation on a relative basis. Clearly in some climates and applications the actual impact on costs will be less, while in others it will be greater depending on the actual climatic variations. This analysis was carried out utilizing an ADL computer simulation which generates annual collector efficiencies using actual weather tapes for different areas in the country.

For this analysis three different collector types were utilized. Figure 6-1 shows the instantaneous efficiency curves for these three collectors. The baseline, two pane, flat black collector is representative of today's low-temperature collectors. The one pane, selective, evacuated collector is a collector which is not actually marketed today. Its characteristics, however, match closely those of the Corning evacuated tube collector. It is, in effect, a continuous model of an evacuated tube collector which has discrete tubes. A third collector, the concentrating collector, is based on Suntec's SLATS collector. Using these collector efficiency curves, the ADL computer simulation was run for Albuquerque and Boston for the months of December and June and different outlet temperatures and average collector efficiencies on a monthly basis were obtained. These results are plotted in Figure 6-2. It can be seen that the data for the different months fall on approximately the same line. We, therefore, assumed that these curves for the two months shown are representative of the other months of the year. In order to simplify the analysis, the curves for Boston and Albuquerque were averaged producing a single curve. The average annual insolation on a surface at an angle equal to the latitude is 750,000 Btu's per year per square foot for Albuquerque and 500,000 Btu's per square foot per year for Boston. We therefore used an average insolation figure of 625,000 Btu's per square foot per year to match the averaged collector curves obtained from Figure 6-2. These average curves are shown in Figure 6-3. Finally, using a price of $10./square foot for the baseline collector and $20 per square foot for the evacuated and concentrating collectors we obtained the curves shown in Figure 6-4, which relate the cost to collect one million Btu's per year to the storage temperature. We then used this curve to estimate the cost of a collector system for different storage systems requiring different storage temperatures.

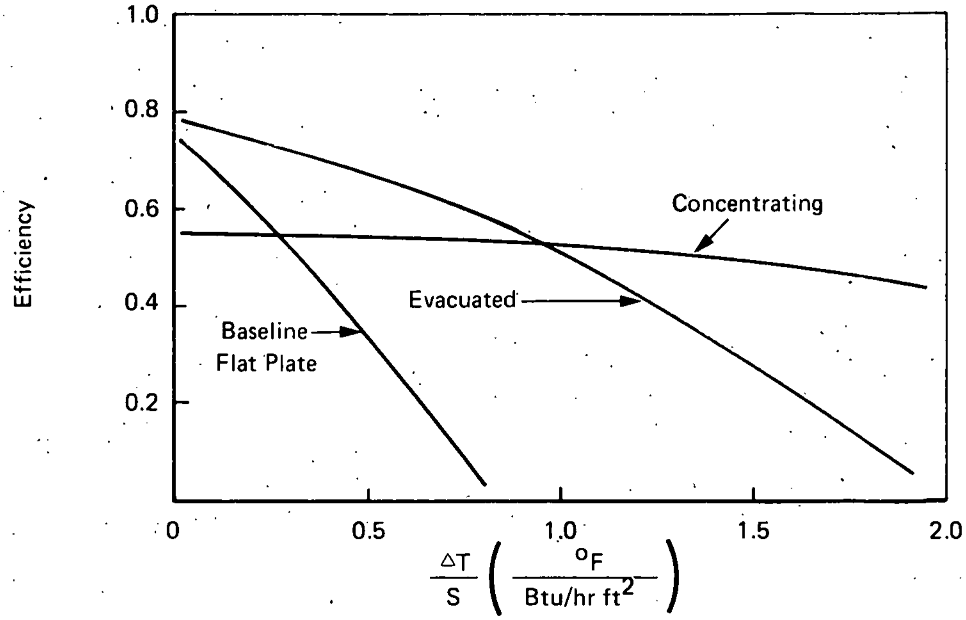


FIGURE 6–1 INSTANTANEOUS COLLECTOR EFFICIENCIES

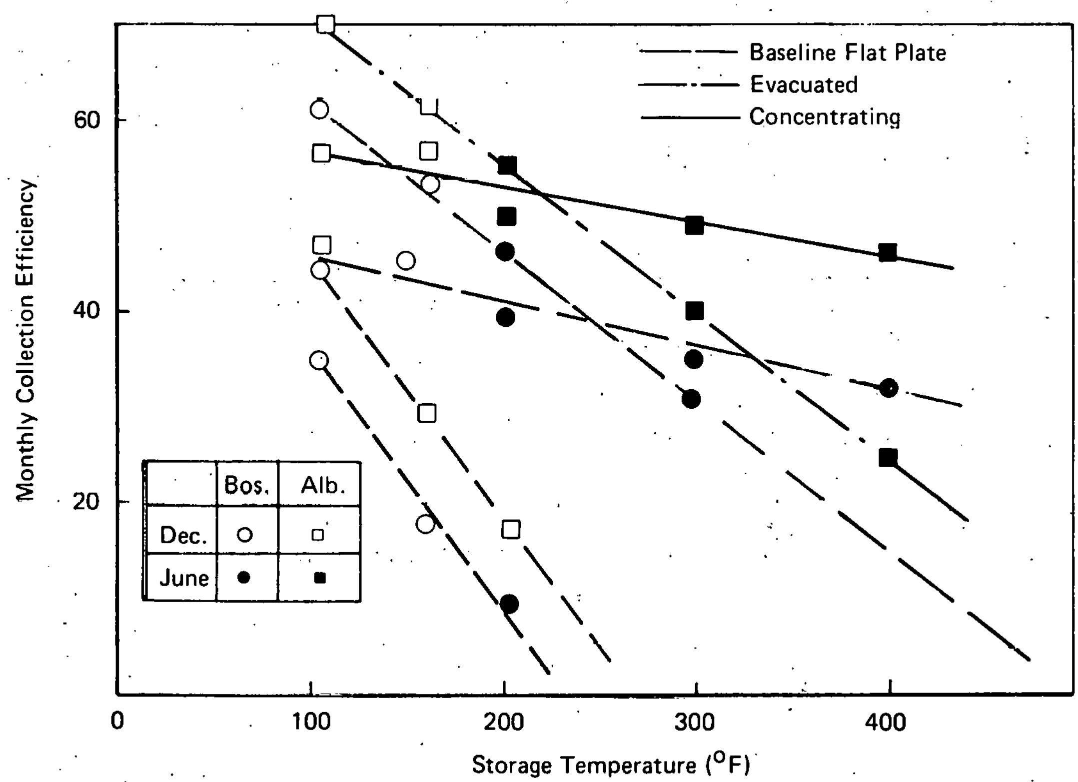
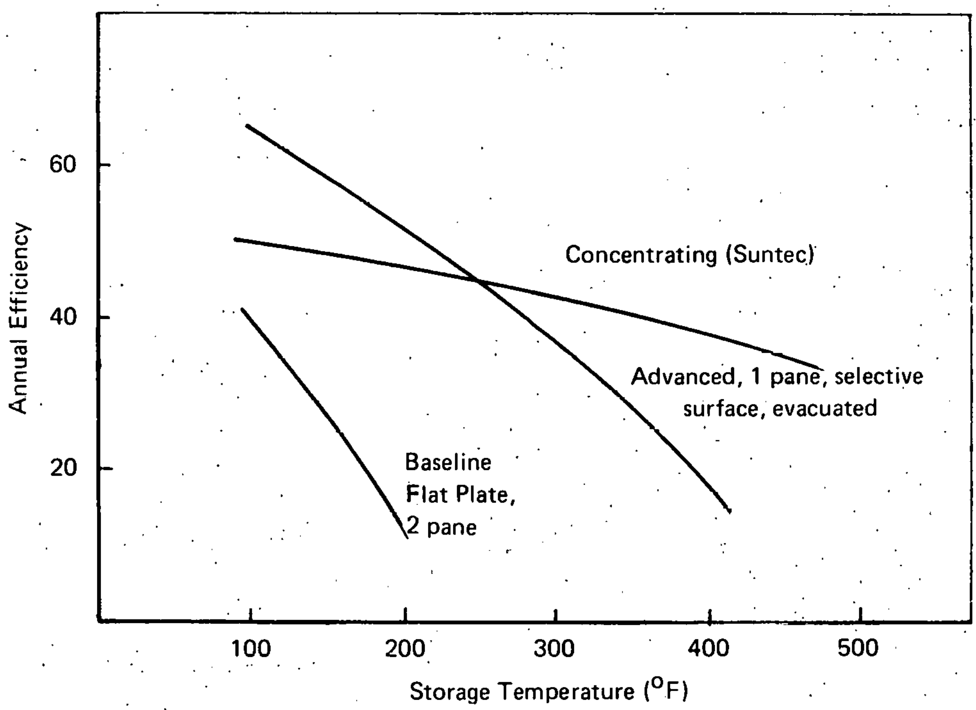
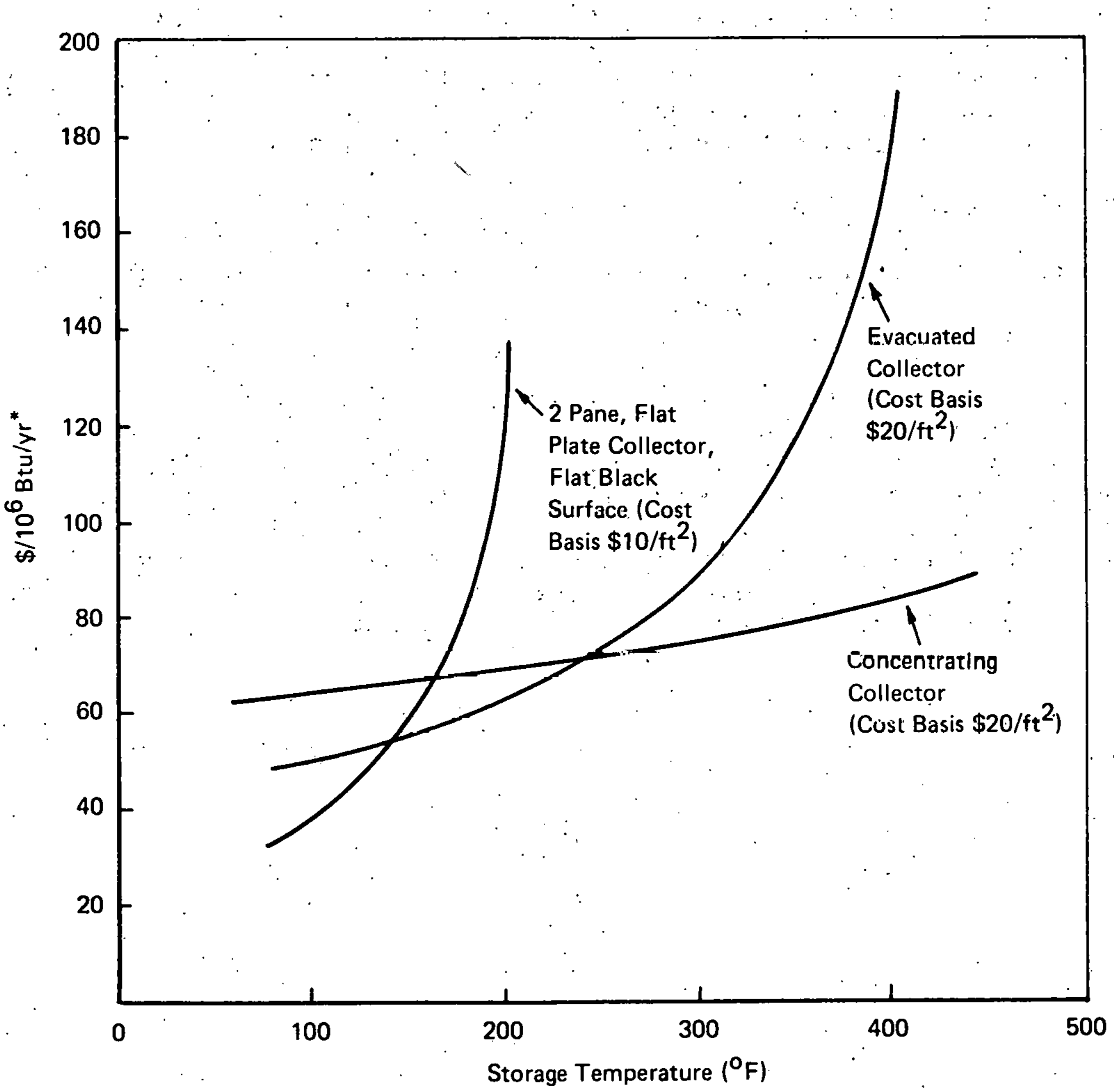


FIGURE 6–2 MONTHLY COLLECTOR EFFICIENCIES FROM ADL COMPUTER SIMULATION



Note: Curves represent mean of Boston and Albuquerque using ADL model.

FIGURE 6–3 AVERAGE ANNUAL COLLECTOR EFFICIENCY AS A FUNCTION OF COLLECTOR OUTPUT TEMPERATURE



* Assumes 625,000 Btu/yr. ft^2

FIGURE 6–4 COST OF COLLECTOR TO CAPTURE 10^6 Btu/yr FOR DIFFERENT STORAGE TEMPERATURES

Table 6-1 summarizes the collector costs for solar input systems other than chemical heat pumps which were costed. The first section contains residential sized storage systems. In general, the cost for solar collectors, except for the University of Delaware, are all equal to or greater than the baseline case. As these storage systems all had initial costs (except for the University of Delaware) greater than the cost of the baseline system, the solar collector costs tend to increase the cost differential. In addition, the collector costs are four to ten times greater than the cost of the baseline system. Thus, this differential solar collector cost in many cases overwhelms any smaller differences in costs between the storage systems themselves.

The other group of storage systems includes only the Monsanto System for storing high temperature heat for absorption air conditioners. In this case the baseline collector and the Monsanto collector costs are the same so that the original comparison of cost is unaffected by the collector cost.

It should be noted that these numbers were based on average values and may unfairly penalize applications in areas where the annual collector efficiency is higher than the average. However, the general trend of cost increases due to the use of higher collection temperatures will apply regardless of the collector efficiency used and, because of the magnitude of the cost differences, even a substantial improvement in average collector efficiency would still involve a substantial collector cost penalty for the higher temperature storage systems.

TABLE 6-1

COLLECTOR COSTS FOR ADVANCED TES TECHNOLOGIES IN REFERENCE APPLICATIONS

CODE #	CONTRACTOR	TEMP (°F)	STORAGE CAPACITY (Btu)	$/10^6 Btu/yr @ STORAGE TEMP.	COLLECTOR COST* ($)
Residential Sized Systems for Space Heating					
B	Baseline	160	400,000	57	8320
11	DOW	170	"	59	8610
12	Clemson	160	"	57	8320
13	U of D	110	"	42	6130
Residential Sized Systems for Space Cooling					
B	Baseline	300	250,000 (Hot side)	75	5475
14	Monsanto	285	"	73	5329

* To fill storage in one day if daily collection equal to annual rate ÷ 365 days.

6.3 Effect of External Costs on Coolness Storage for Off-Peak Use

The baseline system for coolness storage of off-peak electricity utilizes ice melting at 32°F, while the advanced system proposed utilizes an immiscible fluid system which has a melting point of 43°F. This differential in melting point has two different influences on the cost external to the storage module. First, there is an initial hardware cost differential,which results from the requirement for a compressor with a higher horse power rating to deliver the same cooling capability and second there is an off-setting cost advantage to the ice system since it can use a smaller heat exchanger in the cooling duct due to its lower storage temperature. Utilizing the procedure for estimating heat exchanger cost, described in Appendix B, we projected a cost differential of $42 dollars for the system costed during this program. For a compressor sized to meet these requirements, we estimate that the cost differential for the compressor operating at the colder temperatures will be about $200. This gives a net differential in favor of the Franklin Institute System of $150. in hardware costs.

In addition to this differential, there will be an on-going cost savings resulting from the use of the warmer storage temperature. This can be estimated as follows. Figure 6-5 presents a curve relating EER to evaporator temperature for the Westinghouse PD05A model compressors. We have used this model as the basis for operating cost comparisons. The suction temperature (Freon temperature in the evaporator) for the ice storage is approximately 20°F while the suction temperature for the Franklin Institute case is estimated to be 35°F with an 8° differential between the suction temperature and the melting temperature of the storage material. From the curve for the Westinghouse model shown, the EER is 8.5 for the lower suction temperature and 10.6 for the higher temperature. This is equivalent to an operating difference of 8.6 watts input. In order to estimate the value of this energy input differential, we have used data from ORNL*, which projects energy use for central air conditioners. This data projects a value of 4,390 kilowatt hours per year usage for an average residential air conditioner in the year 1985. Since the 45° operating temperature for the Franklin Institute System is representative of a typical compressor system without storage, its hourly consumption can be used to calculate operating time of 1330 hours per year. This gives a kilowatt hour/year differential of 1,085. Using a cost for electricity of 4¢ per kilowatt hour gives a cost savings of approximately $43. a year. Based on the cost differential between the two systems as summarized in Table 6.2, this operating savings will yield a payback period for the additional costs of the energy conserving Franklin Institute module of 4 years. This is a reasonable value to promote commercialization of the system and future cost reductions could make the design even more attractive.

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* Eric Hirst, Oak Ridge National Laboratory, personal communication, 1978.

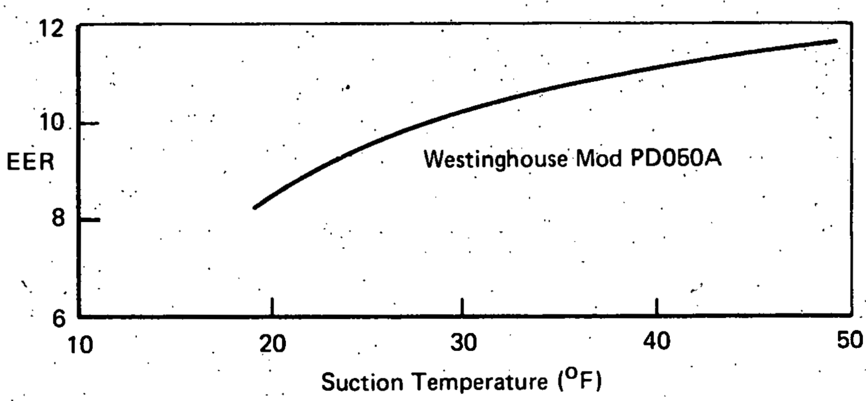


FIGURE 6–5 EFFICIENCY OF COMPRESSOR AS A FUNCTION OF SUCTION TEMPERATURE

TABLE 6-2

OPERATING AND INITIAL COST
DIFFERENTIALS FOR COMPLETE OFF-PEAK COOLNESS STORAGE SYSTEMS

	Cost of Storage ($) Module	Hardware Differential ($)	Total Differential ($)	Years to Pay Back @ $42/yr
Baseline	1170	--	--	
Franklin Institute	1487	-150	+167	4

CHAPTER 7

CHEMICAL HEAT PUMP ANALYSIS

7.1 Introduction

In order to provide a valid basis for comparing the cost of a chemical heat pump system with an equivalent baseline system, an analysis was carried out to determine the characteristics of a baseline and chemical heat pump system that would meet the same design requirements. Both systems were designed to handle heating, cooling, and water heating loads for a residential and commercial case. In one case, diurnal storage systems, which would be capable of meeting 50% of the system loads using solar inputs, were used. In the second case, a 100% seasonal storage system capable of meeting all system loads with solar inputs was used. The analysis considered 3 different geographic areas represented by Boston, Albuquerque, and Forth Worth. The following sections describe in more detail the approach, the basis for the various assumptions, and the results.

7.2 Diurnal Storage Case

7.2.1 Description of Baseline System

The baseline system consisted of an atmospheric water storage system used to provide hot water and space heating directly and an absorption air conditioning unit driven by the hot water to provide space cooling. The characteristics of the Arkla unit used are shown in Figure 7-1. An average cooling COP of 0.7 was used in the analysis. It was assumed that the tank was insulated sufficiently so that standby losses were negligible. The system is shown schematically in Figure 7-2.

In the analysis of the diurnal storage case since a relatively small volume of water was used, it was assumed that the mean collector temperature was 100°F in the winter and 200°F in the summer. These temperatures were utilized with the collector performance curves shown in Section 7.4 to obtain the month input for the different geographic regions. In practice the thermal storage system will cycle through a temperature range and the water returning from the heating or cooling system will be at a temperature 25-30°F below the peak storage temperature. Maintaining stratified storage and pumping cooler water from the bottom of the storage tank to the collector, results in mean collector temperatures equal to or less than these valves. The approach used to obtain the collector area required for a 50% solar system is shown in Table 7-1.

7.2.2 Description of Chemical Heat Pump System

The Rocket Research sulphuric acid storage system was used as the basis for the analysis of chemical heat pumps. The system used is shown schematically in Figure 7-3. During operation the system is charged by boiling sulphuric acid to increase its concentration. Space and water heating are accomplished either by the heat rejected during charging or by discharging.

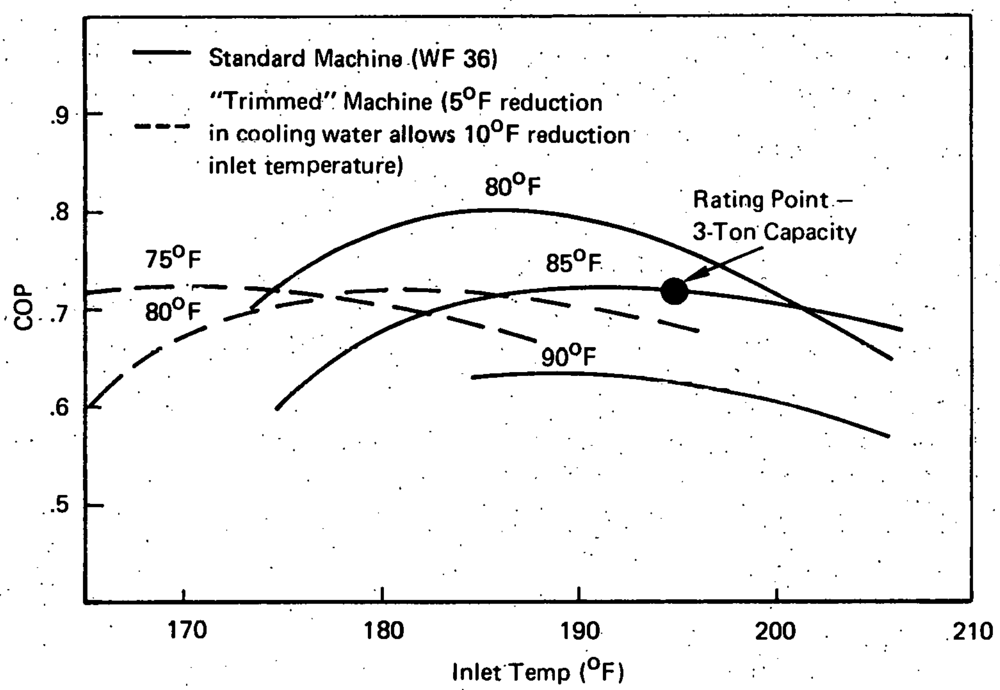
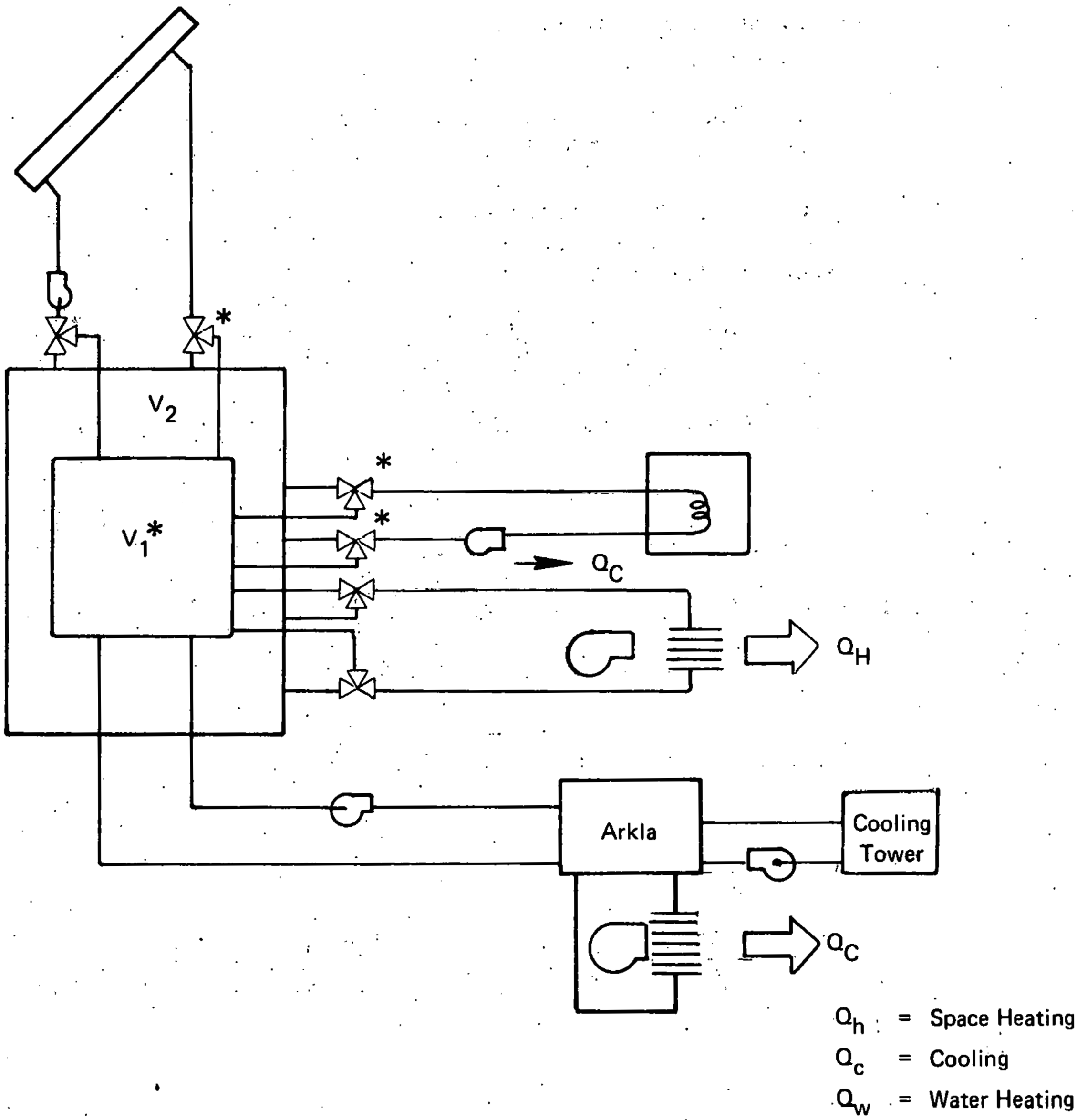


FIGURE 7–1 PERFORMANCE OF ARKLA UNIT MODEL #WF36



* Seasonal storage only; single tank for diurnal.

FIGURE 7–2 SCHEMATIC OF BASELINE SYSTEM USING WATER STORAGE

For each city:

- Assume collector area.

- Assuming cooling C.O.P. of 0.7, calculate total monthly loads from Section 7.4.

- Using collector efficiencies and insolation data from Section 7.4, calculate annual energy collected for mean collector temperatures of:

Boston:	June through September	200°F
	October through May	100°F
Albuquerque:	May through September	200°F
	October through April	100°F
Fort Worth:	March through November	200°F
	December through February	100°F

- Calculate percent of load met by solar.

- Repeat using different area to find percent of load met by solar as a function of area.

- Estimate area required for 50% solar system.

TABLE 7-1 SUMMARY OF METHODOLOGY FOR ESTIMATING DIURNAL PERFORMANCE OF WATER STORAGE SYSTEM

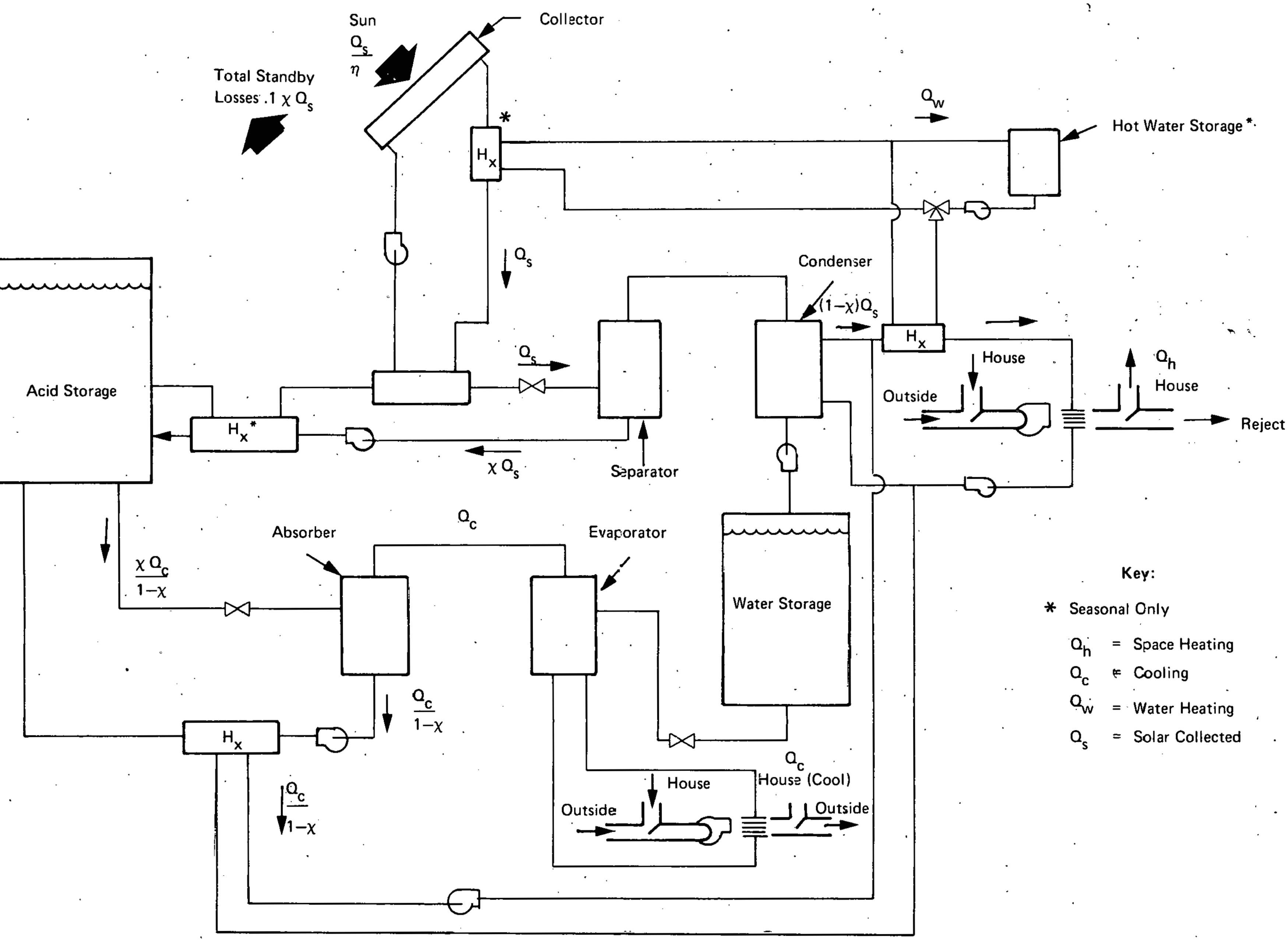


FIGURE 7–3 CHEMICAL HEAT PUMP SYSTEM

The percent of collected energy which goes to the condenser varies with state of charge. In the analysis of the diurnal storage case, we have used a mean value of .45 as suggested by Rocket Research.*

The charging temperature also varies with state of charge. For the diurnal case, mean temperatures of 200°F and 300°F were used to bound the probable range of temperatures.

As in the water storage case, an estimate was made of the collector area required to meet different percentages of the residential load with solar for each city. The approach used is shown in Table 7-2.

7.2.3 Results for Diurnal Storage Case

Using the method described above, percent solar was estimated for several areas. The results are shown in Figure 7-4 and Table 7-3. In some cases at the 200°F mean temperature, the chemical heat pump system requires less collector area. However, the differences are not significant when compared to the cost of the storage module. At high temperatures, the direct solar system requires less collector area due to the reduced collector efficiencies.

For the commercial case, similar results would occur. Although the cooling load is a higher percentage of the total load than the residential case, the poorer cooling COP of the CHP system will offset any gain from the slightly reduced collector efficiency of the water storage system.

7.3 Seasonal Storage Case

7.3.1 Description of Baseline System

For the seasonal storage system two tanks were assumed. One tank was maintained between a temperature of 180 and 200°F and the other tank was maintained at a temperature of less than 200°F. The hot tank was used for providing cooling. Space heating and water heating were taken from either tank depending on the appropriate temperatures. Two tanks were used in this case, because of the difficulty of raising a large tank to the temperature required for air conditioning on a short-term basis. It was assumed that the hot tank was positioned inside the cooler tank so that standby losses were dependent only on the temperatures of the outside tank. The system was insulated to give a heat loss of less than 2 $Btu/hr/ft^2$ on an annual basis. This is achieved using 5 inches of urethane foam insulation. Again, cooling was accomplished by using an Arkla absortion unit with a COP of 0.7. The residential and commercial loads and the collector efficiencies used are discussed in Section 7.4.

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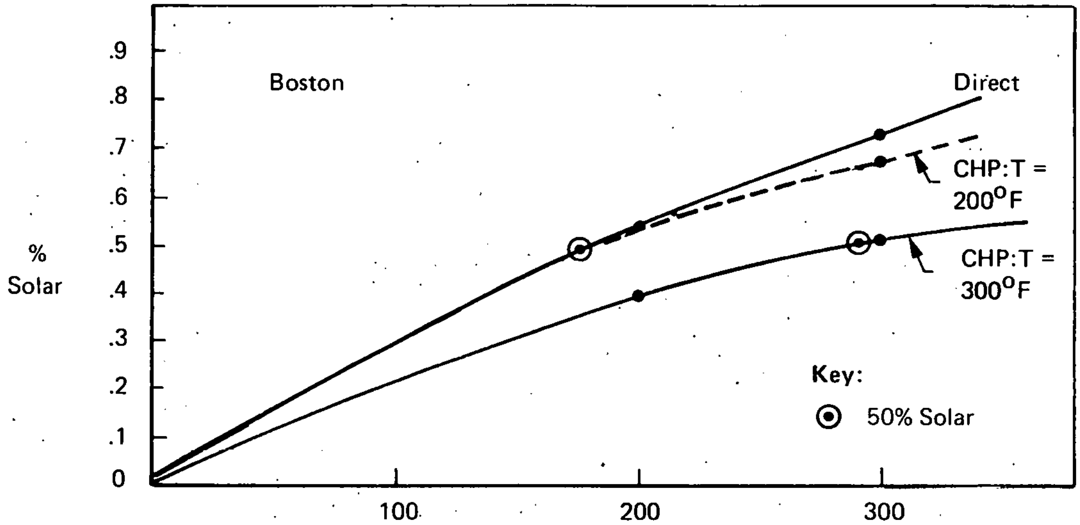
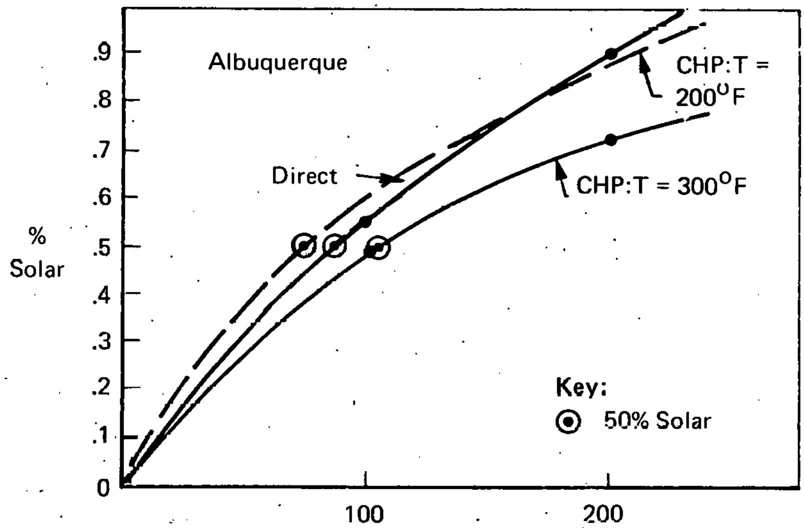
* E. C. Clarket al., Sulfuric Acid and Water Chemical Heat Pump/Chemical Energy Storage Program. Contract 18-495 B/Sandia Corporation 1978.

For each city:

- Assume collector area.
- Use mean value of 55% of collected energy to storage and 45% to low temperature sink.
- For each month assume as much as 1.45 times collected energy can be used for space and water heating if required.
- For each month assume as much as 0.45 times collected energy can be used for cooling if required.
- Calculate annual energy collected using monthly collector efficiencies and insolation data from Section 7.4 and mean collector temperatures of 200°F and 300°F to bound probable range.
- Calculate percent of load met by solar.
- Repeat using different area to find percent of load met as a function of area.
- Estimate area required for 50% solar system.

TABLE 7-2 SUMMARY OF METHODOLOGY FOR ESTIMATING DIURNAL PERFORMANCE OF CHEMICAL HEAT PUMP SYSTEM





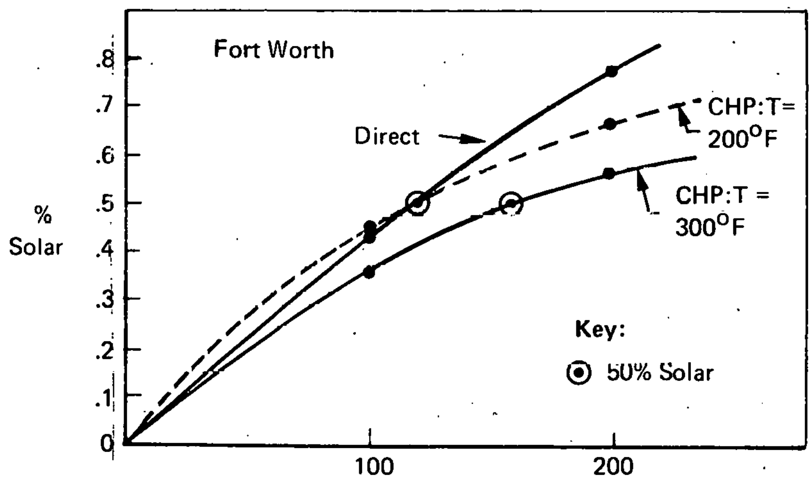


FIGURE 7–4 COLLECTOR AREA AS A FUNCTION OF PERCENT SOLAR FOR RESIDENTIAL CASE WITH DIURNAL STORAGE

	Area (ft^2)	Calculated % Solar		Area (ft^2) for 50% Solar from Figure 7-6		
		Direct Solar	CHP	Direct Solar	CHP T=300°F	CHP T=200°F
Boston	200 300	.54 .72	.40 .51	185	270	185
Albuquerque	100 200	.56 .92	.48 .73	90	102	74
Fort Worth	100 200	.40 .78	.37 .56	125	158	115

TABLE 7-3 RESULTS FOR RESIDENTIAL APPLICATION USING DIURNAL STORAGE

The approach used to estimate required area and storage capacity is shown in Figure 7-5. The methods begin by guessing collector area, storage volumes, and storage initial temperature for a starting month. At least 1 week's storage for the worst cooling month is required. Next, using the collector efficiency for the initial temperature, the energy collected in the next month is calculated. The loads including standby losses are subtracted from the collected energy and new temperatures are calculated. These temperatures are used to estimate the collector efficiency for the next month and the process above is repeated. All months are treated in this way. Finally the initial temperatures are compared with the final values and the temperature excursion of the two storage containers during the year is examined. If the temperatures are the same and the water storage temperature has cycled between the limits given above, the solution has been found. If not, new guesses are made and the process repeated.

7.3.2 Description of Chemical Heat Pump System

The chemical heat pump system used is similar to that shown in Figure 7-3. In the seasonal storage case, however, the system includes a heat exchanger to recover some of the energy which would ordinarily be lost in the charging of the system, due to the fact that a large storage tank is used. In addition, because of the requirement for meeting 100% of the loads, a heat exchanger for heating hot water running directly off the solar collector is utilized. This also requires the use of a larger water storage tank than would be used in the diurnal system. In order to carry out the analysis, the characteristics of the chemical heat pump system were represented by the curves shown in Figures 7-6 and 7-7 and the appropriate value selected for each month depending on the state of charge. These assumed a minimum condensing temperature of 130°F to provide domestic hot water.

The method of solution is shown in Figure 7-8. An initial guess of the required storage, the collector area and the percent of charge on the first month is made. Then the program steps through on a month-by-month basis using the percent of charge to obtain the collector temperature and corresponding efficiency. A unique solution is found when the storage unit cycles from zero to 100 percent charged and the final percent charged is the same as the initial guess.

7.3.3 Seasonal Storage Results

The two seasonal storage models described above were computerized and solutions found for the residential and commercial loads shown in Section 7.4. The results are shown in Table 7-4. In all cases but Boston-residential, less collector area was required by the CHP system. Boston water storage was better, because of the extremely poor collector performance at elevated temperatures during the winter months when the residential load (space heating) peaks.

For the costing portion of this project "representative" values were obtained by arithmetically averaging the three cities. These values are also shown in Table 7-4.

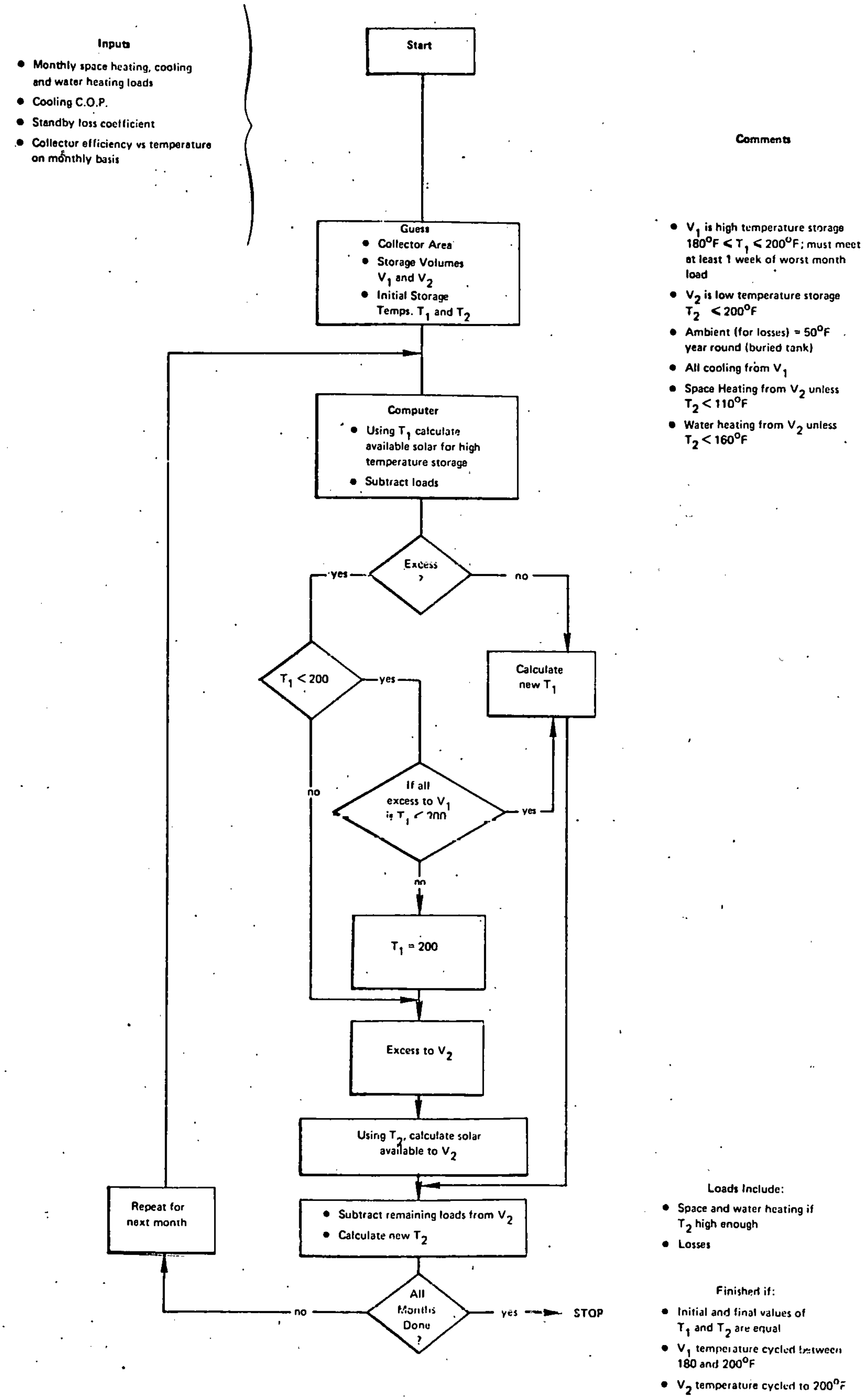
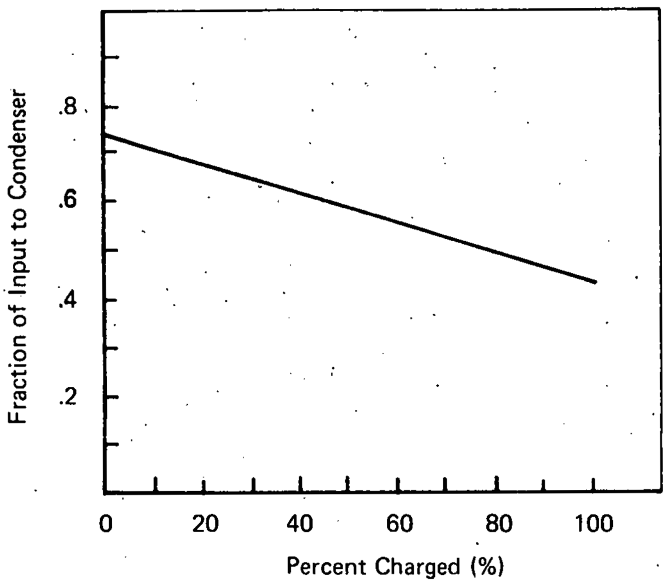
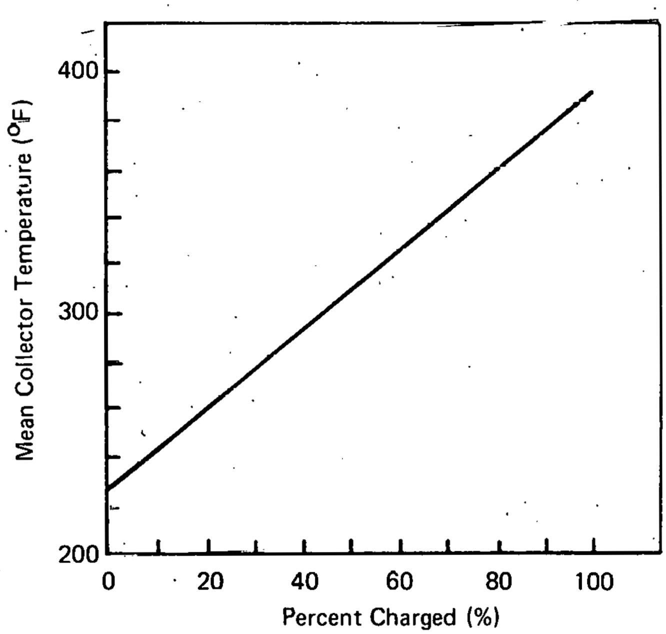


FIGURE 7–5 FLOW CHART OF SEASONAL STORAGE ANALYSIS METHODOLOGY FOR BASELINE CASE



Source: ADL estimates based on E.C. Clark et al. *Sulfuric Acid and Water Chemical Heat Pump/Chemical Energy Storage Program.* Contract 18–495B, Sandia Corporation, 1978.

FIGURE 7–6 FRACTION OF SOLAR ENERGY COLLECTED WHICH GOES TO STORAGE AS A FUNCTION OF PERCENT OF STORAGE AVAILABLE



Source: Arthur D. Little, Inc., estimates based on E.C. Clark et al. *Sulfuric Acid and Water Chemical Heat Pump/Chemical Energy Storage Program.* Contract 18–495B, Sandia Corporation, 1978.

FIGURE 7–7 MEAN COLLECTOR TEMPERATURE AS A FUNCTION OF PERCENT OF STORAGE AVAILABLE

Inputs	Program Steps	Comments
• Monthly Space Heating, Water Heating and Cooling Loads (Section 7.4)	• Guess Total Storage Content Required (BTU's)	
	• Guess Percent of Storage Available for Starting Month	
• Collector Efficiency vs. Temperature (Mean) on Monthly Basis (Section 7.4)	• Guess Collector Area	
• Mean Collector Temperature vs. Percent Storage Available (See Figure 7.7)	• Calculate Collector Temperature	• Assumes State of Change at Beginning of Month Applies for Whole Month
	• Calculate Collected Solar from Corresponding Efficiency	
• Instantaneous COP vs. Percent Storage Available (See Figure 7.6)	• If State of Charge is such that Condensing Temperature is Less than 150°F (Percent Charge Less than 22) and the Heating Load is Greater than Zero, take Water Heater from Direct Solar	
• Standby Loss as Percent of Energy to Storage (10%)		
• Monthly Insolation (Section 7.4)		
	• If Condensing Temperature is Greater than 150°F or H = 0 use as much of Condenser Heat as Possible for Space and/or Water Heating	• When H = 0 Assume it is Summer and Water Heated While Supplying Air Conditioning
	• Take Balance plus Cooling Load from Storage	
	• Calculate Percent Charge at End of Month	
	• Repeat for All Months	
	• If Final % Charge Same as Initial Guess <u>and</u> Storage Cycled from 0 to 100% Charged During Year Solution Finished <u>otherwise</u> Make New Guesses and Repeat	

FIGURE 7-8 CHEMICAL HEAT PUMP SEASONAL STORAGE ANALYSIS METHODOLOGY

	Baseline: Water Storage			Chemical Heat Pump		
	Collector Area (ft^2)	Storage (ft^3)		Collector Area (ft^2)	C.O.P.	Storage (10^6 Btu)
		Hot	Warm			
Boston						
Residential	576	1,160	4,775	590	1.14	9.05
Commercial	5,563	22,100	23,500	3,910	1.56	36.00
Albuquerque						
Residential	257	1,780	2,250	202	1.21	5.60
Commercial	3,025	81,500	37,500	2,280	1.25	65.50
Fort Worth						
Residential	365	2,600	2,170	334	0.90	9.00
Commercial	5,334	65,600	51,000	3,765	1.16	98.8
Value Used in Costing						
Residential	400	1,850	3,048	375	-	8.0
Commercial	4,641	56,400	37,300	3,318	-	65.0

TABLE 7-4 ESTIMATES OF STORAGE SIZE AND COLLECTOR AREAS FOR BASELINE AND CHEMICAL HEAT PUMP SEASONAL STORAGE SYSTEMS

7.4 Description of Load Data Used

In order to estimate the performance of the two different types of storage systems in real applications it is necessary to make estimates of typical residential and commercial loads for the three different regions. For the residential case, the space heating and cooling loads were estimated assuming a heating load of 10,000 Btu's/°day and cooling loads of 15,000 Btu's/°day for a typical residence. Using degree days heating and degree days cooling data from published references for Boston, Albuquerque and Fort Worth, typical heating and cooling loads were projected. The water heating load was calculated based on HUD recommendations for solar water heating systems. These criteria are summarized in Table 7-5 and the actual data is shown in Table 7-6 for the three cities considered.

Commercial loads were estimated by scaling the residential load curves to include proportionally higher air conditioning loads based on the ratio of air conditioning and space heating loads to total loads for typical residential and apartment buildings drawing on Arthur D. Little, Inc., proprietary data. The water heating load was estimated at 20 times the residential use. This is consistent with the HUD* design requirements for a 20-unit apartment building. The final load curves used for this analysis are shown in Figures 7-9, 7-10, and 7-11.

In order to estimate the actual energy collected in these different regions, a typical solar collector was selected and the collector efficiency estimated as a function of collector temperature for different months for the different cities. The actual method used in making these estimates was the $\bar{\phi}$ method, which has been described by Klein.** The solar collector used was an Owens Illinois Sunpac concentrating collector with characteristics shown in Figure 7-12. Utilizing this instantaneous collector efficiency curve and the solar incidence value shown in Table 7-6, the data shown in Figure 7-13 was obtained for the different cities. These were used to calculate the total energy collected in any month during the analysis described above. ***

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* Sheet Metal and Air Conditioning Manufacturers' Association. Fundamentals of Solar Heating. Correspondence course prepared for the Department of Energy under contract EG-77-C-01-4038. Reprinted August 1978.

** Klein, S.A., "Calculation of Flat Plate Collector Utilizability," Solar Energy 21(5): 393-402, 1978.

***The $\bar{\phi}$ method is most accurate when collector inlet temperatures are reasonably constant. Wide swings about mean temperatures may give actual efficiency values which are lower than those shown. Therefore, the seasonal estimates are more accurate than the diurnal.

Residential (Single Family Dwelling)

- Heating

Heating Degree Days[1]/Month x 10,000 $\frac{\text{Btu}}{\text{Degree Day}}$

- Cooling

Cooling Degree Days[2]/Month x 15,000 $\frac{\text{Btu}}{\text{Degree Day}}$

- Water Heating[3]

70 gallons/day through 90°F rise

Commercial (20 Unit Apartment Building)

- Heating and Cooling

ADL Estimates based on proprietary data

- Water Heating

20 Times Residential Use[3]

(1) U.S. Department of Commerce, Environmental Sciences Service Administration, Environmental Data Service. Climatic Atlas of the United States. June 1968.

(2) Conway Research, Inc., 1972 Site Selection Handbook, Vol. 2, Industry Guide to Environmental Planning. Pages 231-284, 1972.

(3) Sheet Metal and Air Conditioning Contractors' Association. Fundamentals of Solar Heating. Correspondence course prepared for the Department of Energy under Contract EG-77-C-01-4038. Reprinted August 1978.

TABLE 7-5 BASIS OF ESTIMATED BUILDING LOADS

TABLE 7-6 BOSTON CLIMATIC & LOAD DATA (Residential)

MONTH	SOLAR INCIDENCE (1) 10^3 Btu/Ft^2	DEGREE DAYS COOLING (2)	DEGREE DAYS COOLING (3)	HEATING LOAD (4) 10^6 Btu	COOLING LOAD (COLD Btu) (5) 10^6 Btu
Jan	23.74	1088	-0-	10.88	-0-
Feb	27.69	972	-0-	9.72	-0-
Mar	37.16	846	-0-	8.46	-0-
Apr	39.90	513	-0-	5.13	-0-
May	45.27	208	6	2.08	0.09
Jun	46.72	36	155	0.36	2.33
Jul	47.53	-0-	269	-0-	4.035
Aug	44.21	9	271	0.09	4.065
Sep	42.57	60	132	0.60	1.98
Oct	37.66	316	15	3.16	0.23
Nov	22.88	603	1	6.03	0.02
Dec	20.74	983	-0-	9.83	-0-
TOTAL	436.07	5634	849	56.34	12.75

NOTES:

(1) Solaron Corporation. Application Engineering Manual. Edition No. 3, October 1978, pp. 110.23-110.64.

(2) U.S. Department of Commerce, Environmental Sciences Service Administration, Environmental Data Service. Climatic Atlas of the United States. June 1968.

(3) Conway Research, Inc. 1972 Site Selection Handbook, Vol. 2, Industry Guide to Environmental Planning. 1972, pp. 231-284.

(4) Heating Load = (10,000) (DDH)

(5) Cooling Load = (15,000) (DDC)

(6) Hot Water Load = (70,000) (8.35) (30)
= 1.58 x 10^6 Btu/Mo.
= 18.9 x 10^6 Btu/Yr.

TABLE 7-6 (Continued)

ALBUQUERQUE CLIMATIC & LOAD DATA (Residential)

MONTH	SOLAR (1) INCIDENCE 10^3 Btu/Ft^2	DEGREE (2) DAYS COOLING	DEGREE (3) DAYS COOLING	HEATING (4) LOAD 10^6 Btu	COOLING (5) LOAD (COLD Btu) 10^6 Btu
Jan	52.03	930	-0-	9.30	-0-
Feb	53.81	703	-0-	7.03	-0-
Mar	66.48	595	5	5.95	0.075
Apr	68.29	288	-0-	2.88	-0-
May	70.40	81	26	0.81	0.39
Jun	67.59	-0-	277	-0-	4.155
Jul	66.92	-0-	414	-0-	6.21
Aug	68.43	-0-	282	-0-	4.23
Sep	67.25	12	149	0.12	2.235
Oct	66.18	229	-0-	2.29	-0-
Nov	54.94	642	-0-	6.42	-0-
Dec	49.54	868	-0-	8.68	-0-
TOTAL	751.86	4348	1153	43.48	17.295

NOTES:

(1) Solaron Corporation. Application Engineering Manual. Edition No. 3, October 1978, pp. 110.23-110.64.

(2) U.S. Department of Commerce, Environmental Sciences Service Administration, Environmental Data Service. Climatic Atlas of the United States. June 1968.

(3) Conway Research, Inc. 1972 Site Selection Handbook, Vol. 2, Industry Guide to Environmental Planning. 1972, pp. 231-284.

(4) Heating Load = (10,000) (DDH)

(5) Cooling Load = (15,000) (DDC)

(6) Hot Water Load = (70,000) (8.35) (30)
= 1.58×10^6 Btu/Mo.
= 18.9×10^6 Btu/Yr.

TABLE 7-6 (Continued)

FORT WORTH CLIMATIC & LOAD DATA (Resdential)

MONTH	SOLAR INCIDENCE 10^3 Btu/Ft^2 (1)	DEGREE DAYS COOLING (2)	DEGREE DAYS COOLING (3)	HEATING LOAD 10^6 Btu (4)	COOLING LOAD (COLD Btu) 10^6 Btu (5)
Jan	34.70	614	-0-	6.14	-0-
Feb	37.80	448	6	4.48	0.09
Mar	48.98	319	21	3.19	0.315
Apr	47.80	99	71	0.99	1.065
May	52.81	-0-	195	-0-	2.925
Jun	55.47	-0-	546	-0-	8.19
Jul	58.42	-0-	606	-0-	9.09
Aug	58.39	-0-	456	-0-	6.84
Sep	52.15	-0-	382	-0-	5.73
Oct	49.46	65	171	0.65	2.565
Nov	38.83	324	36	3.24	0.54
Dec	34.23	536	1	5.36	0.015
TOTAL	569.03	2405	2491	24.05	37.365

NOTES:

(1) Solaron Corporation. Application Engineering Manual. Edition No. 3, October 1978, pp. 110.23-110.64.

(2) U.S. Department of Commerce, Environmental Sciences Service Administration, Environmental Data Service. Climatic Atlas of the United States. June 1968.

(3) Conway Research, Inc. 1972 Site Selection Handbook, Vol. 2, Industry Guide to Environmental Planning. 1972, pp. 231-284.

(4) Heating Load = (10,000) (DDH)

(5) Cooling Load = (15,000) (DDC)

(6) Hot Water Load = (70,000) (8.35) (30)
= 1.58×10^6 Btu/Mo.
= 18.9×10^6 Btu/Yr.

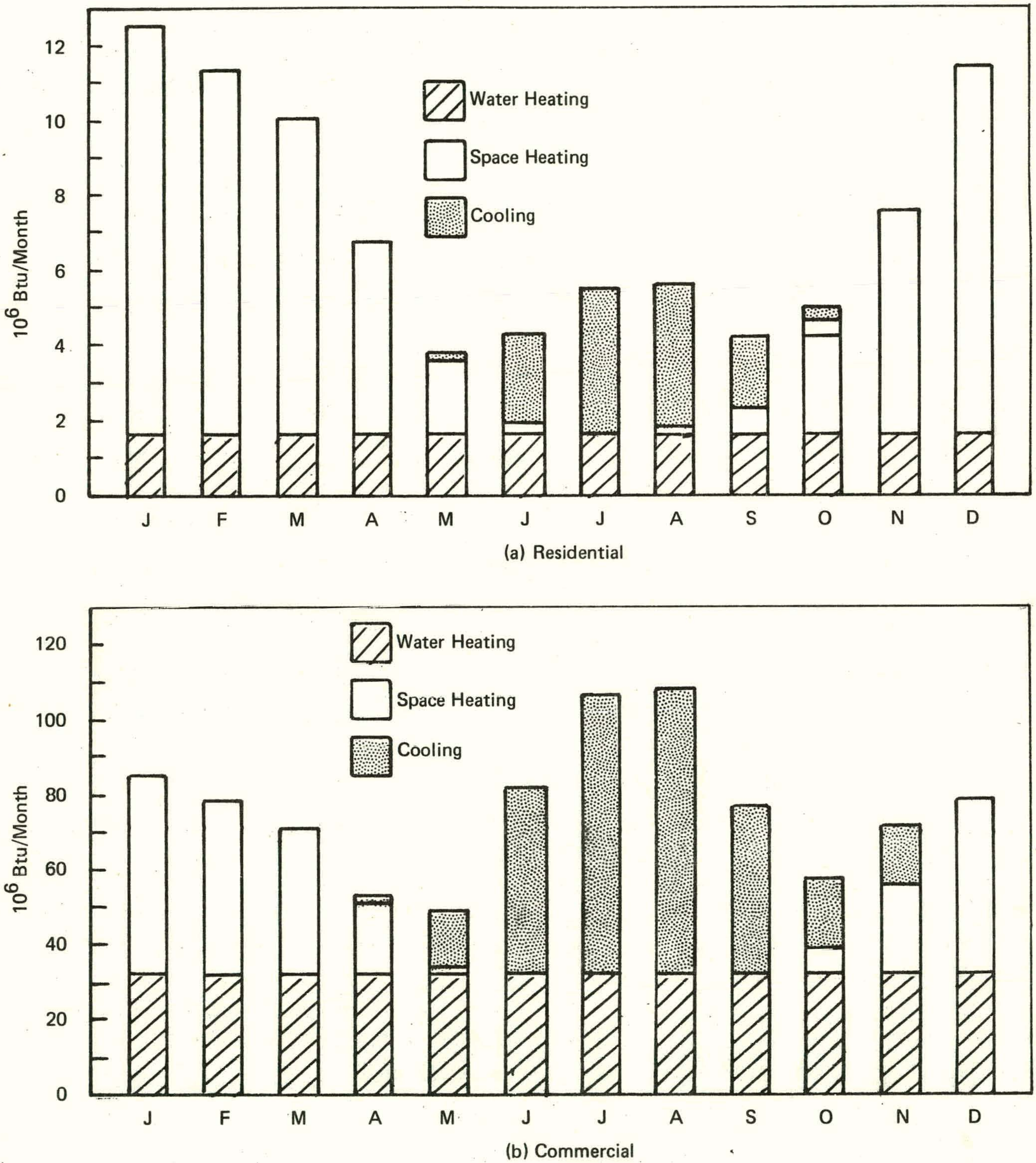


FIGURE 7–9 MONTHLY SPACE HEATING, COOLING, AND WATER HEATING LOADS FOR BOSTON

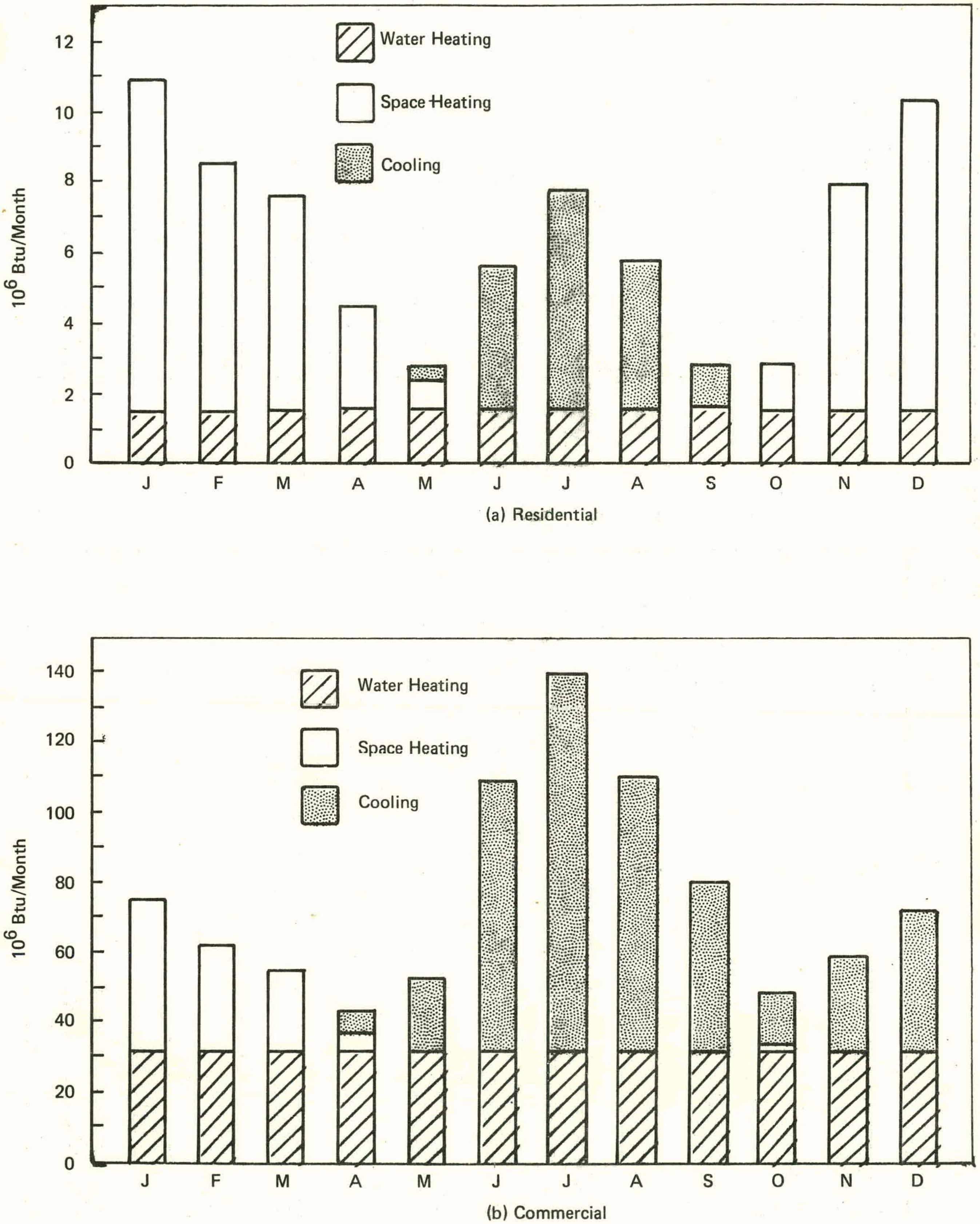


FIGURE 7–10 MONTHLY SPACE HEATING, COOLING, AND WATER HEATING LOADS FOR ALBUQUERQUE

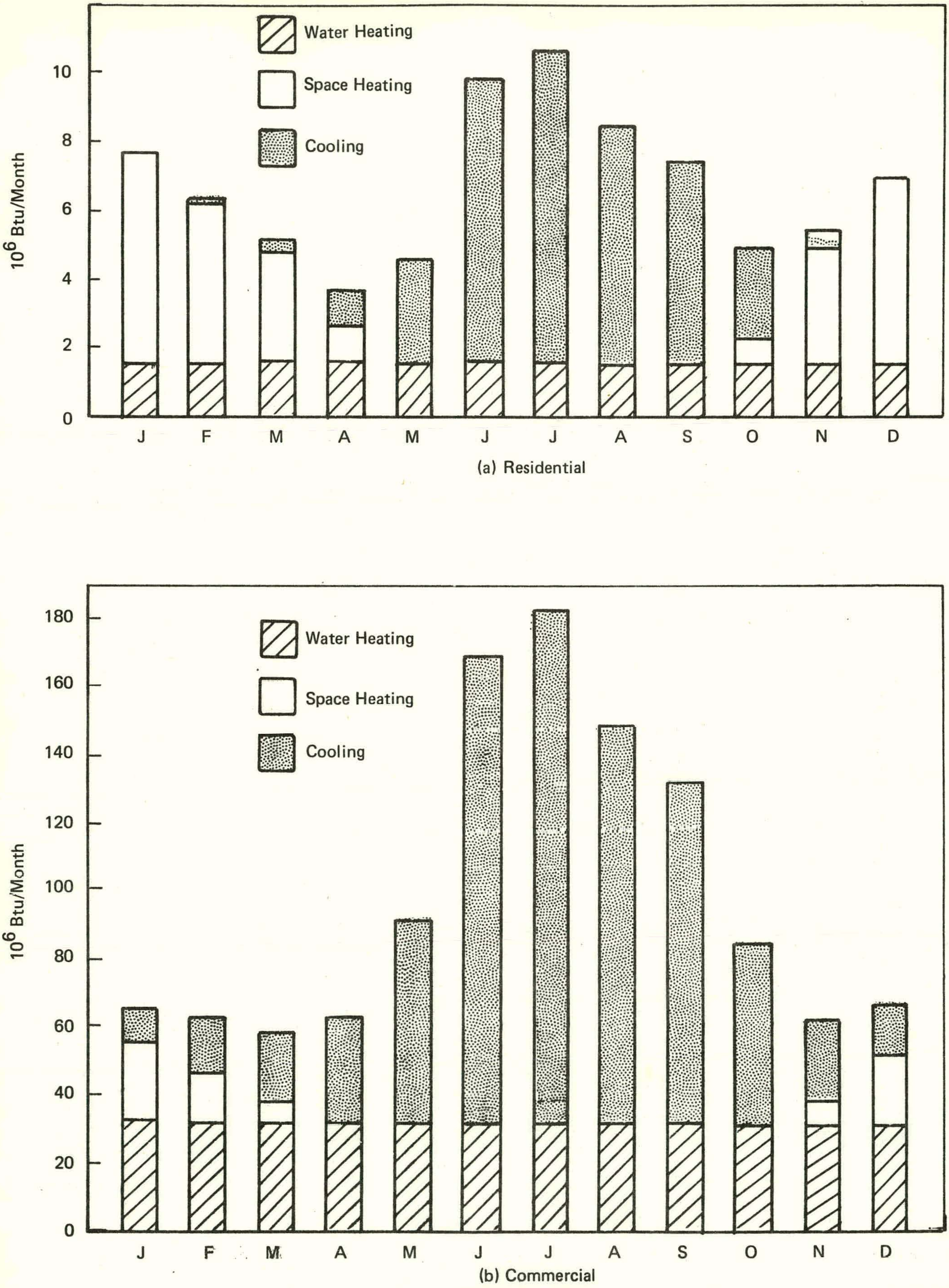
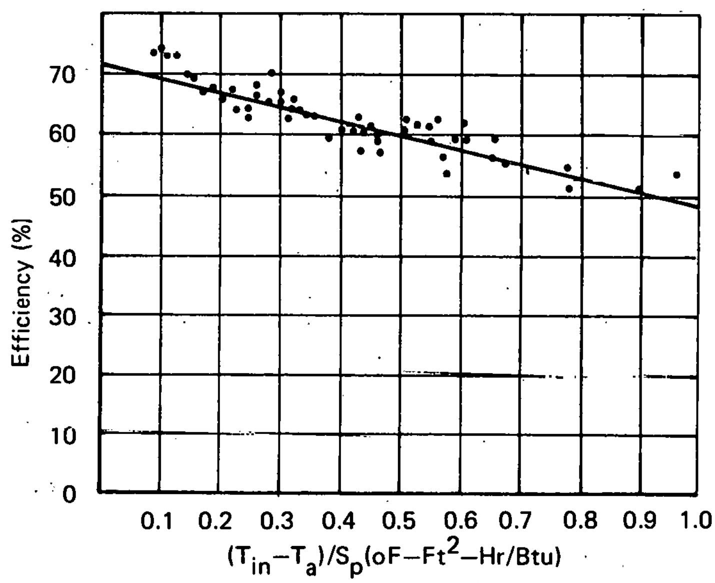
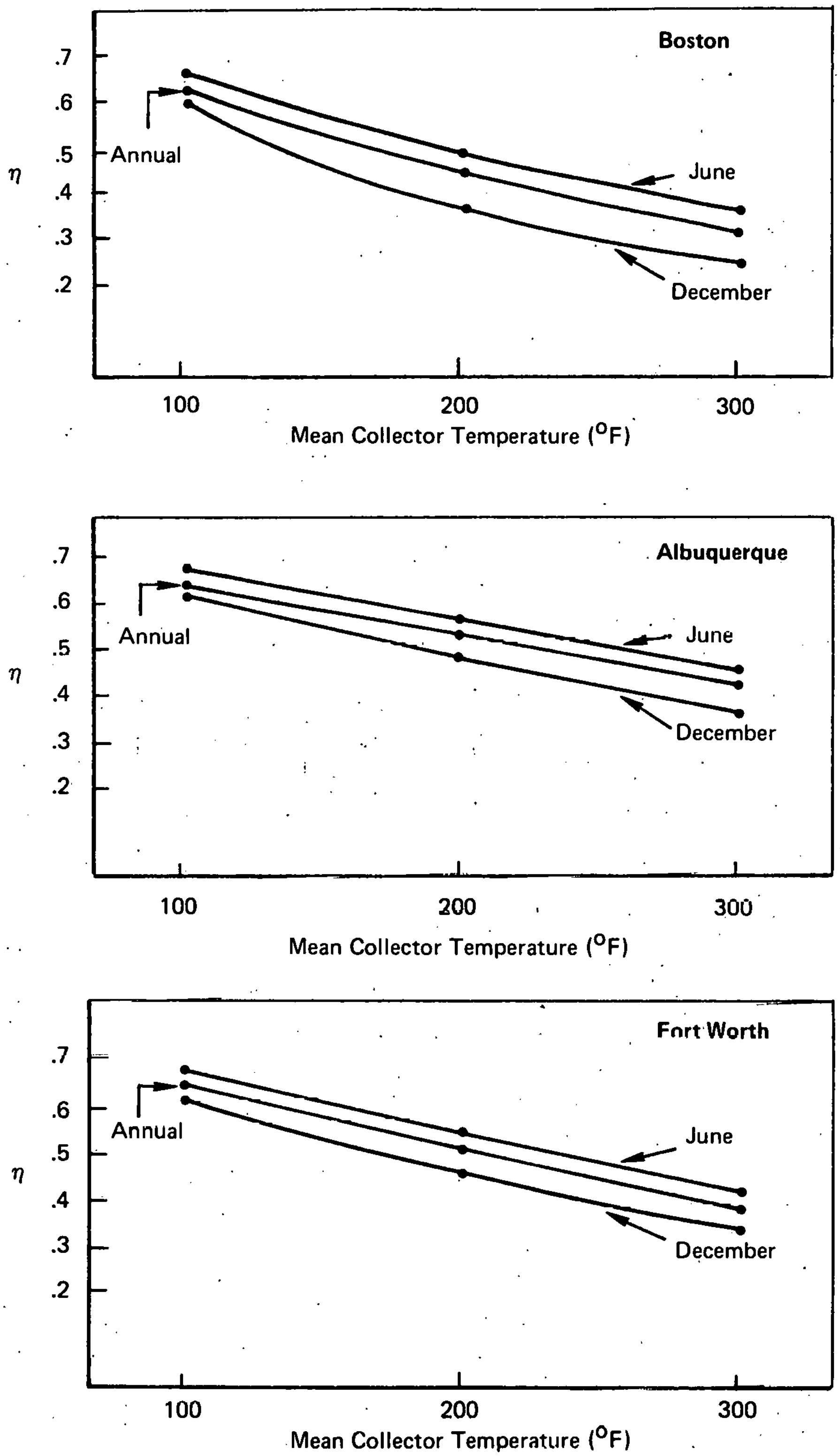


FIGURE 7–11 MONTHLY SPACE HEATING, COOLING, AND WATER HEATING LOADS FOR FORT WORTH



Source: Owens–Illinois Sales Literature

FIGURE 7–12 INSTANTANEOUS COLLECTOR EFFICIENCY



Source: Arthur D. Little, Inc. Estimates based on $\bar{\phi}$ method.

FIGURE 7–13 COLLECTOR EFFICIENCY AS A FUNCTION OF TEMPERATURE

APPENDIX I

BACK-UP DATA ON COSTS OF SYSTEM ELEMENTS

APPENDIX I.A

STORAGE MEDIA

SYSTEM	MATERIAL	QUANTITY (lbs)	COST BASIS ¢/LB	COST ($)	SYSTEM TOTAL ($)
A1					
EIC Corp.	CH_3OH	17,500	8.2	1440	-
	$CaCl_2$	28,000	5	1400	
					$2840
A2					
EIC Corp.	CH_3OH	17,500	8.2	1440	
	$CaCl_2$	28,000	5	1400	
					$2840
A3					
Martin Marietta	Ammonia	7854 gallons	6	4550	
	Compound B	71,420	3*	2143	
					$6700
A4					
Rocket Research	H_2SO_4 (93%)	131625	3	3949	
	H_2SO_4 (10%)	65700	.5	329	
					$4278

* Price supplied by Martin Marietta

APPENDIX I.A (Continued)

STORAGE MEDIA

SYSTEM	MATERIAL	QUANTITY (lbs)	COST BASIS ¢/LB	COST ($)	SYSTEM TOTAL ($)
A5					
Rocket Research	H_2SO_4 (93%)	16,200	3	486	
	H_2SO_4 (10%)	8,085	.5	40	
					$526
A6					
Rocket Research	H_2SO_4 (93%)	16,200	3	486	
	H_2SO_4 (10%)	8,085	.5	40	
					$526
A7					
Rocket Research	H_2SO_4 (93%)	810	3	24	
	H_2SO_4 (10%)	404	.5	2	
					$ 26

APPENDIX I.A (Continued)
STORAGE MEDIA

SYSTEM	MATERIAL	QUANTITY (lbs)	COST BASIS ¢/LB	COST ($)	SYSTEM TOTAL ($)
A8 University of Delaware	$NaSO_4 \cdot 10H_2O$	1,920	1.3	25	-
	Borax	90	20	18	-
	Thickener	180	3	5	-
	$NaCl_2$	187	3	6	-
	KCl	187	3	6	60
A9 Franklin Institute	22%(wt) Aqueous Trimethylamine	400 (1835 lbs Sol)	7	128	12,128
A10 Dow Chemical Co.	$Mg(NO_3) \cdot 6H_2O$	3276	16	524	52,524
A11 Dow Chemical Co.	$Mg(NO_3) \cdot 6H_2O$	3273	16	524	--
	NH_4NO_3	3273	6	196	72,720

APPENDIX I.A (Continued)
STORAGE MEDIA

SYSTEM	MATERIAL	QUANTITY (lbs)	COST BASIS ¢/LB	COST ($)	SYSTEM TOTAL ($)
A12 Clemson University	$Na_2S_2O_3.5H_2O$	4440	12	533	533
A13 University of Delaware	$Na_2SO_4,10H_2O$	3520	1.3	46	-
	Borax	120	20	24	-
	Min-U-Gel	360	3	11	81
A14 Monsanto Research	Polyethylene	2210	29	641	-
	Ethylene Glycol	1590	25	398	1039
A15 Suntek	Block	16.5	3	.50	-
	$CaCl_2 \cdot 6H_2O$	25	2.5	.62	-
	Nucleating Agent	.6	12	.08	-
	Epoxy	1	100	1.00	-
	Total/block			2.20	
	Fabrication including filling block & sealing		5	.05	
	Total for 276 blocks			2.25	621

APPENDIX I.A (Continued)
STORAGE MEDIA

SYSTEM	MATERIAL	QUANTITY (lbs)	COST BASIS ¢/LB	COST ($)	SYSTEM TOTAL ($)
A16 Brookhaven National Lab.	Block	25	-	.45	-
	$CaCl_2 \cdot 6H_2O$	6.25	2.5	156	-
	Microencapsulation	6.25	70	4.75	
	Total/Block			4.981	4981
	Total for 1,000 blocks				

APPENDIX I.B
CONTAINER

Key Code		Description	Cost per System
B1	a)	$CaCl_2$ salt container (tank only) 2 vacuum tanks at 3200 gallons each with flanged ends for salt bed access. 2 @ $6850	$19,464
	b)	Methanol container 2660 steel vacuum tank (insulated) $5764	
B2	a)	$CaCl_2$ salt container (tank only) 2 vacuum tanks at 3200 gallons each with flanged ends for salt bed access. 2 @ $6850	$19,464
	b)	Methanol container 2660 gallon steel vacuum tank $5764	
B3	a)	High temperature reactors 2 tanks @ 4400 gallons (from Appendix II) $4780 each	$20,490
	b)	Hx 4800 ft steel tubing 1" plus fabrication 2 @ $2760	
	c)	Ammonia condensate receiver 5280 gallons (from Appendix II) $5410	
B4	a)	8125 gallon water storage tank unpressurized steel with ZRC lining $4073	$21,497
	b)	15,440 gallon unpressurized steel tank with liner $9024	
	c)	Glass-lined Pfaudler tanks for absorber and separator 2 @ $4200	

APPENDIX I.B (Continued)

CONTAINER

Key Code		Description	Cost per System
B5	a)	1000 gallon Nalgene polethylene tank with cover and support - $1150	$4,598
	b)	1900 gallon unpressurized steel tank with liner $2438	
	c)	Glass lined tanks (Pfaudler) for absorber and separator, 50 gallons 2 @ $500	
B6	a)	1000 gallon Nalgene polyethylene tank with cover and supports $1160	$21,320
	b)	1900 gallon (Pfaudler) glass lined steel tank $11760	
	c)	Glass lined (Pfaudler)tanks for absorber and separator 320 gallons 2 @ $4200	
B7	a)	50 gallon Nalgene polyethylene tank with cover and support $58	$ 2,008
	b)	95 gallon (Pfaudler) glass lined tank $950	
	c)	50 gallon glass lined (Pfaudler) tanks for absorber and separator $500 each.	

CONTAINER

Key Code	Description	Cost per System
B8	a)Plastic stacking racks - $75 b)Plastic film for chubs - $15 c)Plywood encloser - $38 d)Ducting - $28 e)Cost of making chubs - $86	242
B9	a)350 gallon mild steel tank with welded in steel mesh and a jacket to protect insulation	246
B10	a)1800 .224' dia. x .63' high aerosol cans and contract filling of these cans - $450 b)22 gauge galvanized steel sheets for outer shell - $200 c)Diffusers and spacers - $14 d)2 units of ducting 12'x12' of 1' length - $19	683
B11	a)3600 .224' dia. x .63' high aerosol cans and contract filling of these cans - $900 b)22 gauge galvanized steel sheets for outer shells - $372 c)Diffusers and spacers - $16 d)2 units of ducting 12"x12" of 1' length - $19	1,307
B12	a)Unpressurized steel tank 350 gallons with lining b)Diffuser - $3	363
B13	a)Plastic stacking racks - $100 b)Plastic film for chubs - $20 c)Plywood enclosure - $56 c)Ducting - $28 e)Cost of making chubs - $115	
B14	a)450 gallon 30 psi steel tank with 7 concentric internal steel baffles. Cost includes outer jacket to protect insulation.	$ 2,261

APPENDIX I.C

INSULATION

REFERENCE # AND VENDOR	WHERE INSULATION USED	TEMP (°F)	AREA (FT^2)	PRICE ($/ft.^{2})	COST/SYSTEM ($)
C1 EIC Corporation	$CaCl_2$ Container	270°F	854	.30	$256
	Methanol tank (included with tank)				
					$256
C2 EIC Corporation	$CaCl_2$ Container (outdoors)	270°F	854	2.40	$2050
	Methanol tank (included with tank)				
					$2050
C3 Martin Marietta	2 tanks outdoors	300°F	450	2.60	$2340
	1 tank outdocrs	12C°F	700	1.25	875
					$3215
C4 Rocket Research	Absorber & Separator	400°F	75	.60	$ 45
	Glass Heat Exchanger	400°F	8	.60	5
					$ 50

APPENDIX I.C (Continued)

INSULATION

REFERENCE # AND VENDOR	WHERE INSULATION USED	TEMP (°F)	AREA (FT^2)	PRICE (\$/ft.^{2})	COST/SYSTEM (\$)
C5 Rocket Research	Absorber & Separator	400°F	35	.60	$21
	Glass Heat Exchanger	400°F	25	.50	15
					$36
C6 Rocket Research	Absorber & Separator	400°F	75	.60	$45
	Glass Heat Exchanger	400°F	25	.60	15
	Acid Storage Tank	400°F	250	.60	150
	Water Storage Tank	130°F	145	.15	22
					$232
C7 Rocket Research	Absorber & Separator	400°F	35	.60	$ 21
	Glass Heat Exchanger	400°F	8	.60	5
	Acid Storage Tank	400°F	30	.60	18
	Water Storage Tank	130°F	20	.15	3
					$ 47

APPENDIX I.C (Continued)
INSULATION

REFERENCE # AND VENDOR	WHERE INSULATION USED	TEMP (°F)	AREA (FT^2)	PRICE ($\$/ft^2$)	COST/SYSTEM ($)
C8 University of Delaware	Plywood Enclosure	40	108	.14	15
C9 Franklin Institute	Tank	35	75	.14	11
C10 Dow Chemical	Sheet Metal Enclosure	250	134	.30	40
C11 Dow Chemical	Sheet Metal Enclosure	170	250	.20	50
C12 Clemson University	Tank	135	80	.18	14
C13 University of Delaware	Plywood Enclosure	110	160	.14	22
C14 Monsanto Research	Steel Tank & Expansion Tank	300	99	.35	35
C15 Suntek	Beadwall	N.A.	245	6.00	1472

APPENDIX I.D

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D1	EIC Corporation	Finned Tube: Condensing Methanol to air - Methanol condenses @ 113°F. Air in @ 80°F, out at 105°F 22,200 CFM 6×10^5 Btu/hr	3100	$1865
		Finned Tube: Ethylene Glycol to air Ethylene Glycol in @ 140°F, out @ 160°F Air in @ 70°F, out @ 100°F • 1×10^6 Btu/hr. • 30700 CFM • 148 gpm	1125	$ 788
		Finned Tube: Air to evaporating methanol. Air in @ 50°F, out @ 30°F methanol evaporating @ 20°F • 6×10^5 Btu/hr • 27650 CFM	1725	$1115
		Heat Exchanger in $CaCl_2$ tanks 9200 ft finned tubing + supports, boxes, & assembly	-	$20,710
		Shell and Tube: Methanol vapor to Ethylene Glycol methanol in @ 180°F, out @ 160°F Ethylene Glycol in @ 100°F, out @ 140°F • 200,000 Btu/hr	400	$2620
				$27,098

APPENDIX I.D (Continued)

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D2	EIC Corporation	Finned Tube: Condensing methanol to air methanol condenses @ 113°F Air in @ 80°F out @ 105°F • 35,000 Btu/hr • 1290 C.F.M.	181	$274
		Finned Tube: Ethylene Glycol to air. Ethylene glycol in @ 140°F out @ 160°F air in @ 70°F out @ 100°F • 50,000 Btu/hr • 1536 C.F.M. • 7.4 gpm	56	$205
		Finned Tube: Air to evaporating methanol. Air in @ 50°F, out @ 30°F methanol evaporating @ 20°F • 35,000 Btu/hr. • 1,613 CFM	101	$230
		Heat Exchanger in $CaCl_2$ tanks 1840 ft finned tubing + supports, boxes, and assembly	-	$8,570
		Shell and Tube: Methanol vapor to Ethylene Glycol. Methanol vapor in @ 180°F, out @ 160°F. Ethylene Glycol in @ 150°F. out @ 170°F • 10,000 Btu/hr.	20	$340
				$ 9,620

APPENDIX I.D (Continued)

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D3	Martin Marietta	Note exchanger in HTR included with tank		
		Condenser: Ammonia to Glycol Ammonia condensing @ 115°F -Glycol in @ 85°F, out @ 110°F 49 gpm Heat Exchange Rate: 6×10^5 Btu/hr.	238	$1700
		Evaporator: Glycol to Ammonia Ammonia evaporating @ 20°F -Glycol in @ 45°F, out @ 25°F 62 gpm Heat Exchange Rate 6×10^5 Btu/hr.	255	$1800
		Heating Coil: Glycol to air Glycol in @ 125°F, out @ 100°F 118 gpm Air in @ 70°F, out @ 100°F 31400 CFM 1×10^6 Btu/hr.	2090	$1315
		Condensing Reject Heat Coil: Glycol to air- Glycol in @ 110°F out @ 85°F 57 gpm Air in @ 80°F, out @ 95°F 37,000 CFM $.6 \times 10^6$ Btu/hr.		

APPENDIX I.D (Continued)

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D3 (Cont.)	Martin Marietta	Cooling Coil: Air to Glycol. Air in @ 70°F, out @ 55°F 3700 CFM Glycol in @ 25°F, out @ 45°F 62 gpm .6 X 10^6 Btu/hr.	933	$ 683
		Water Heating Unit: Ammonia vapor: Glycol (assume U = 5 Btu/hr ft^2°F) Ammonia in @ 200°F, out @170°F Glycol in @ 150°F, out at 190°F Heat Exchange rate = 100,000 Btu/hr.	450	$2900
			Total	$12,000

APPENDIX I.D (Continued)

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D4	Rocket Research	Shell and Tube (Glass: Ethylene Glycol- Sulphuric Acid Ethylene Glycol: In @ 105°F, out @ 115°F • 300 gpm Sulphuric Acid: In @ 130°F, out @ 110°F. Area = 650 ft^2 @ 44/ft^2 $28,600 • 130 gpm	650	$28,600
		Shell and Tube Evaporator Water: Boiling @ 350°F. Eythylene Glycol: In @ 50°F, out at 38°F • 6 X 10^5 Btu/hr. • 150 gpm	812	$ 4,756
		Shell and Tube Condenser Water: Condensing @ 130°F Ethylene Glycol: In @ 105°F, out @ 115°F • 6 X 10^5 Btu/hr. • 119 gpm	250	$ 1,767
		Shell and Tube (Glass) Recuperator Sulphuric Acid to Sulphuric Acid Sulphuric Acid, in @ 70°F, out @ 155°F Sulphuric Acid, in @ 215°F, out @ 130°F	74	$ 3,267

APPENDIX I.D (Continued)

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D4 (Cont.)	Rocket Research	Shell and Tube Water Heater Vapor to Ethylene Glycol Vapor in @ 180°F, out @ 160°F Ethylene Glycol in @ 100°F, out @ 140°F • 200,000 Btu/hr.	400	$ 2,620
		Shell and Tube Water Heater Ethylene Glycol to Ethylene Glycol Ethylene Glycol, in @ 220°F, out @ 180°F Ethylene Glycol in @ 100°F, out @ 140°F • 200,000 Btu/hr. • 15 gpm	12.5	$ 265
		Finned Tube: Ethylene Glycol to Air Ethylene Glycol in @ 120°F, out @ 105°F Air, in at 80°F, out @ 110°F • 1 X 10^6 Btu/hr. • 119 gpm • 30,720 CFM	6333	$ 3,627
		Finned Tube: Ethylene Glycol to Air Ethylene Glycol, in @ 50°F, out @ 80°F, Air, in @ 70°F, out @ 55°F. • 6 X 10^5 Btu/hr. • 150 gpm • 36,870 CFM	3200	$ 1,919
			Total	$46,820

APPENDIX I.D (Continued)

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D5	Rocket Research	Shell and Tube (Glass): Ethylene Glycol - Sulphuric Acid Ethylene Glycol: In @ 105°F, out @ 115°F Sulphuric Acid: In @ 130°F, out @ 110°F. • 50,000 Btu/hr • Ethylene Glycol 15 gpm • H_2SO_4 6.5 gpm	37.5	$1,782
		Shell and Tube Evaporator Water: Boiling @ 35°F Ethylene Glycol: In @ 50°F, out @ 38°F • 35,000 Btu/hr • 8.7 gpm	47.4	$ 551
		Shell and Tube (Glass): Recuperator Sulfuric Acid, - Sulphuric Acid Sulfuric Acid, in @ 70°F, out @ 155°F Sulfuric Acid, in @ 215°F @ 215°F, out @ 130°F	13.5	$ 594
		Shell and Tube Condenser: Water condensing @ 130°F Ethylene Glycol, in @ 105°F, out @ 115°F • 35,000 Btu/hr. • 6.9 gpm	14.6	$ 288

APPENDIX I.D (Continued)

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D5 (Cont.)	Rocket Research	Shell and Tube Water Heater Vapor to Ethylene Glycol Vapor in @ 180°F, out @ 160°F Ethylene Glycol in @ 100°F, out @ 140°F • 10,000 Btu/hr.	20	$343
		Shell and Tube Water Heater Ethylene Glycol to Ethylene Glycol Ethylene Glycol: in @ 220°F, out @ 180°F Ethylene Glycol: in @ 100°F, out @ 140°F. • 10,000 Btu/hr. • 1 gpm	1	$ 66
		Finned Tube: Ethylene Glycol to air Ethylene Glycol, in @ 120°F, out @ 105°F Air in @ 80°F, out @ 110°F • 50,000 Btu/hr • 6.9 gpm • 1536 CFM	317	$348
		Finned Tube: Ethylene Glycol to air Ethylene Glycol, in @ 120°F, out 105°F Air in @ 80°F, out @ 110°F • 35,000 Btu/hr. • 818 • 2150	187	$277
				$4249

APPENDIX I.D

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D6	Rocket Research	Shell and Tube (Glass): Ethylene Glycol- Sulphuric Acid Ethylene Glycol: In @ 105°F, out @ 115°F. • 300 gpm Sulphuric Acid: In @ 130°F, out @ 110°F. Area = 650 ft^2 @ \$44/ft^2 \$28,600 • 130 gpm	650	\$28,600
		Shell and Tube Evaporator Water: Boiling @ 35°F Ethylene Glycol: In @ 50°F, out @ 38°F. • 6 X 10^5 Btu/hr. • 150 gpm	812	\$ 4,756
		Shell and Tube Condenser Water: Condensing @ 130°F Ethylene Glycol: In @ 105°F, out @ 115°F. • 6 X 10^5 Btu/hr. • 119 gpm	250	\$ 1,767
		Shell and Tube Water Heater: Vapor to Ethylene Glycol Vapor in @ 180°F, out @ 160°F Ethylene Glycol in @ 100°F, out @ 140°F. • 200,000 Btu/hr. • 15 gpm	400	\$ 265

APPENDIX I.D (Continued)

HEAT EXCHAGNERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D6	Rocket Research	Shell and Tube Water Heater: Ethylene Glycol to Ethylene Glycol Ethylene Glycol in @ 220°F out @ 180°F. Ethylene Glycol in @ 100°F out at 140°F. • 200,000 Btu/hr • 15 gpm	12.5	$ 265
		Finned Tube: Ethylene Glycol to Air Ethylene Glycol, in @ 120°F, out @ 105°F air; in at 80°F, out @ 110°F. • 1 X 10^6 Btu/hr • 119 gpm • 30720 CFM	6333	3627
		Finned Tube: Ethylene Glycol to air. Ethylene Glycol: In @ 50°F, out @ 38°F. Air, in @ 70°F, out @ 55°F. • 6 X 10^5 Btu/hr. • 150 gpm • 36,870 CFM	3200	$1,919
			TOTAL	$43,554

APPENDIX I.D

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D7	Rocket Research	Shell and Tube (Glass): Ethylene Glycol - Sulphuric Acid. Ethylene Glycol: In @ 105°F, out @ 115°F. Sulphuric Acid: In @ 130°F, out @ 110°F. • 50,000 Btu/hr. • Ethylene Glycol 15 gpm • H_2SO_4 6.5 gpm	37.5	$ 1,782
		Shell and Tube Evaporator Water: Boiling @ 35°F. Ethylene Glycol: In @ 50°F, out @ 38°F. • 35,000 Btu/hr. • 8.7 gpm	47.4	$ 551
		Shell and Tube Condenser Water condensing @ 130°F Ethylene Glycol, in @ 105°F, out @ 115°F. • 35,000 Btu/hr. • 6.9 gpm	14.6	$ 288

APPENDIX I.D (Continued)

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D7	Rocket Research	Shell and Tube Water Heater Vapor to Ethylene Glycol Vapor in @ 180°F, out @ 160°F. Ethylene Glycol in @ 100°F, out @ 140°F. • 10,000 Btu/hr.	20	$ 343
		Shell and Tube Water Heater Ethylene Glycol to Ethylene Glycol Ethylene Glycol: in @ 220°F, out @ 180°F Ethylene Glycol: in @ 100°F, out @ 140°F. • 10,000 Btu/hr. • 1 gpm	1	$ 66
		Finned Tube: Ethylene Glycol to air- Ethylene Glycol, in @ 120°F, out @ 105°F. Air in @ 80°F, out @ 110°F. • 50,000 Btu/hr • 6.9 gpm • 1536 CFM	317	$ 348

APPENDIX I.D (Continued)

HEAT EXCHANGERS

CODE	CONTRACTOR NAME	DESCRIPTION	ESTIMATED AREA	DELIVERED COST/ SYSTEM
D7 (Cont.)	Rocket Research	Finned Tube: Ethylene Glycol to air. Ethylene Glycol, in @ 120°F, out @ 105°F. Air in @ 80°F, out @ 110°F. • 35,000 Btu/hr. • 8.8 gpm • 2150 CFM	187	$ 277
			TOTAL	$3,655
D9	Franklin Institute	Freon evaporator - 3 ton		100
D12	Clemson University	Shell and tube - ethylene glycol-therminol 60 Ethylene glycol: In 140°F; out 130°F; 3.4 gpm Therminol: In 123°F; out 133°F; 32 gpm Young #F808-AR-1P, 50,000 Btu/hr	111	840
D17	Desert Reclamation	Shell and tube: water-water Water: In 35°F; out 60°F; 23,100 gpm Water: In 65°F; out 50°F; 38,600 gpm Patterson Kelly, 3 @ $116,500, 2.88 x 10^8Btu/hr	150,000	350,000
D19	Desert Reclamation	Shell and tube: water-water Water: In 35°F; out 60°F; 800 gpm Water: In 65°F; out 50°F; 1,340 gpm Young #3020-8R-1P, 10 x 10^6Btu/hr	5,192	25,000

APPENDIX I.E

HEAT TRANSFER FLUIDS

Key Code	Contractor	Description	Amount (gallons)	Cost ($)
E1	EIC Corporation	Ethylene glycol	256	512
E2	EIC Corporation	Ethylene glycol	256	512
E3	Martin Marietta	Ethylene glycol	470	940
E4	Rocket Research	Ethylene glycol	125	250
E5	Rocket Research	Ethylene glycol	17	34
E6	Rocket Research	Ethylene glycol	125	250
E7	Rocket Research	Ethylene glycol	17	34
E9	Franklin Institute	Dowtherm J	20	98
E12	Clemson University	Exxon Marcol 172	35	44

APPENDIX I.F

PIPING AND DUCTING

CODE KEY AND CONTRACTOR	PIPE (P) OR DUCT (D) AND SIZE	LENGTH (FT)	COST ($)	TOTAL ($) FOR SYSTEM
F1				
EIC Corporation	P, 2 1/2", Copper	200	920	
	P, 2", Aluminum	50	46	
	P, 1/2" Aluminum	120	19	
	D, 36" X 36"	40	1152	
	D, 24" X 26"	50	1000	
			TOTAL	3137
F2				
EIC Corporation	P, 3/4" Copper	200	140	
	P, 1/2" Aluminum	170	26	
	D, 12" X 12"	90	864	
			TOTAL	1030
F3				
Martin Marietta	P, 1 1/2" dia. Copper	200	430	
	P, 2 1/2" dia. Copper	300	1380	
	P, 3" dia. Steel	100	420	
	P, 1" dia. Steel	250	60	
	D, 36" X 46"	40	1312	
	D, 24" X 36"	50	1200	
			TOTAL	4802
F4				
Rocket Research	P, 2" Duriron	200	1000	
	P, 2 1/2" Copper	200	900	
	P, 2" Copper	200	620	
	D, 36" X 44"	75	2520	
			TOTAL	5040

APPENDIX I.F (Continued)

PIPING AND DUCTING

CODE KEY AND CONTRACTOR	PIPE (P) OR DUCT (D) AND SIZE	LENGTH (FT)	COST ($)	TOTAL ($) FOR SYSTEM
F5				
Rocket Research	P, 1 1/2" Duriron	50	215	
	P, 3/4" Copper	200	140	
	D, 12" X 15"	75	810	
			TOTAL	1155
F6				
Rocket Research	P, 2" Duriron	100	500	
	P, 2 1/2" Copper	200	900	
	P, 2" Copper	200	620	
	D, 35" X 55"	75	2520	
			TOTAL	4540
F7				
Rocket Research	P, 1 1/2" Duriron	50	215	
	P, 3/4" Copper	200	140	
	D, 12" X 15"	75	810	
			TOTAL	1165

APPENDIX I.F (Continued)

PIPING AND DUCTING

CODE KEY AND CONTRACTOR	PIPE (P) OR DUCT (D) AND SIZE	LENGTH (FT)	COST ($)	TOTAL ($) FOR SYSTEM
F9 Franklin Institute	P, 3/4", Steel	20	6	6
F12 Clemson University	P, 1", PVC	10	2	2
F14 Monsanto Research	P, 3/4", Steel	20	6	6
F17 Desert Reclamation	P, 8", Steel	10000	75500	
	P, 30", Steel	1000	36860	112360
F18 Texas A&M	P, 6", PVC	200	5400	
	P, 8", PVC	2300	9223	
	P, 10", PVC	2000	12600	22363
F19 Desert Reclamation	P, 6", Steel	1500	7665	7665

APPENDIX I.G

BLOWERS AND MOTORS

KEY CODE	CONTRACTOR NAME		DESCRIPTION	PRICE PER UNIT	NUMBER OF UNITS PER SYSTEM	DELIVERED COST PER SYSTEM
G1	EIC Corporation	a)	31,400 CFM (air) at 2" static peerless blower P402 DWDI 15 HP motor & drive	$2753	1	$2753
		b)	22,200 CFM (air) - price from curves Appendix II	1935	1	1935
		c)	27,650 CFM (air) price from curves, Appendix II	2289	1	2289
						$6977
G2	EIC Corporation	a)	1536 CFM (air) price from Appendix II	592	1	592
		b)	1290 CFM (air) price from Appendix II	576	1	576
		c)	1610 CFM (air) price from Appendix II	597	1	597
						$1765

APPENDIX I.G (Continued)

BLOWERS AND MOTORS

KEY CODE	CONTRACTOR NAME		DESCRIPTION	PRICE PER UNIT	NUMBER OF UNITS PER SYSTEM	DELIVERED COST PER SYSTEM
G3	Martin Marietta	a)	31,400 CFM (air) at 2" static Peerless Blower #PH02 DWDI, 15 H.P. motor	$2753		$2753
		b)	37,000 CFM (air) @ 2" static pressure from cost curves	5800	2	5800
						$8553
G4	Rocket Research	a)	30,720 CFM 15 hp motor & drive Peerless Blower P402 DWDI	2753	1	2753
		b)	36,870 CFM 20 hp motor & drive (price from Appendix II)	2889	1	2889
						$5642
G5	Rocket Research	a)	1536 CFM 3/4 hp motor & drive (price from Appendix II)	592	1	592
		b)	2150 CFM 1 hp motor & drive (price from Appendix II)	632	1	632
						$1224

APPENDIX I.G (Continued)

BLOWERS AND MOTORS

KEY CODE	CONTRACTOR NAME	DESCRIPTION	PRICE PER UNIT	NUMBER OF UNITS PER SYSTEM	DELIVERED COST PER SYSTEM
G6	Rocket Research	a) 30720 CFM 15 hp motor & drive Peerless Blower P402 DWDI	$2753	1	$2753
		b) 36,870 CFM 20 hp motor & drive (price from Appendix II)	2889	1	2889
					$5642
G7	Rocket Research	a) 1536 CFM 3/4 hp motor & drive (price from Appendix II)	592	1	592
		b) 2150 CFM 1 hp motor & drive (price from Appendix II)	632	1	632
					$1224

APPENDIX I.H

PUMPS AND MOTORS

KEY CODE	CONTRACTOR NAME		DESCRIPTION	PRICE PER UNIT	NUMBER OF UNITS PER SYSTEM	DELIVERED COST PER SYSTEM
H1	EIC Corporation	a)	5 GPM of methanol (100%) at 30' head (constant displacement) Burks close-coupled standard construction	$277	1	$277
		b)	150 gpm Ethylene Glycol price from Appendix II	532	1	532
					TOTAL	$809
H2	EIC Corporation	a)	5 GPM of methanol (100%) at 30' head (constant displacement) Burks close-coupled standard construction	277	1	277
		b)	7.4 gpm ethylene glycol price from Appendix II	260	1	260
					TOTAL	$537
H3	Martin Marietta	a)	118 gpm Ethylene Glycol (from Appendix II)	477		477
		b)	71 gpm Ethylene Glycol (from Appendix II)	396		396
		c)	87 gpm Ethylene Glycol (from Appendix II)	424		424
						$1297

APPENDIX I.H (Continued)

PUMPS AND MOTORS

KEY CODE	CONTRACTOR NAME	DESCRIPTION	PRICE PER UNIT	NUMBER OF UNITS PER SYSTEM	DELIVERED COST PER SYSTEM
H4	Rocket Research	a) 130 gpm conc. Sulphuric Acid, Gould Alloy 20 (2 speed) (basic price + 10%)	$1733	2	$3465
		b) 300 gpm Ethylene Glycol (2 speed)(price from Appendix II)	869	1	869
		c) 150 gpm Ethylene Glycol (price from Appendix II)	532	1	532
		d) 2 gpm condensate pump positive displacement (estimate)	175	1	175
		e) 119 gpm Ethylene Glycol (price from Appendix II)	479	1	479
				TOTAL	$5520

APPENDIX I.H (Continued)

PUMPS AND MOTORS

KEY CODE	CONTRACTOR NAME	DESCRIPTION	PRICE PER UNIT	NUMBER OF UNITS PER SYSTEM	DELIVERED COST PER SYSTEM
H5	Rocket Research	a) 6.5 gpm, conc. Sulphuric Acid, Gould Alloy 20, (2 speed)	$855	2	$1710
		b) 8.7 gpm, Ethylene Glycol (price from Appendix II)	289	1	289
		c) .1 gpm, condensate pump (price estimated)	100	1	100
		d) 6.9 gpm, Ethylene Glycol (price from Appendix II)	286	1	286
		e) 15 gpm, Ethylene Glycol (2 speed) (price from Appendix II)	330	1	330
				TOTAL	$2715

APPENDIX I.H (Continued)

PUMPS AND MOTORS

KEY CODE	CONTRACTOR NAME	DESCRIPTION	PRICE PER UNIT	NUMBER OF UNITS PER SYSTEM	DELIVERED COST PER SYSTEM
H6	Rocket Research	a) 130 gpm conc. Sulfuric Acid, Gould Alloy 20, (2 speed) (base price + 10%)	1733	2	$3466
		b) 300 gpm Ethylene Glycol (2 speed) (price from Appendix II)	869	11	869
		c) 150 gpm Ethylene Glycol (price from Appendix II)	532	1	532
		d) 2 gpm Condensate Pump positive displacement (estimated)	175	1	175
		e) 119 gpm Ethylene Glycol (price from Appendix II)	479	1	479
				TOTAL	$ 5521

APPENDIX I.H (Continued)

PUMPS AND MOTORS

KEY CODE	CONTRACTOR NAME	DESCRIPTION	PRICE PER UNIT	NUMBER OF UNITS PER SYSTEM	DELIVERED COST PER SYSTEM
H7	Rocket Research	a) 6.5 gpm conc. Sulphuric Acid Gould Alloy 20 (2 speed)	$855	2	$1710
		b) 8.7 gpm Ethylene Glycol (price from Appendix II)	289	1	289
		c) .1 gpm condensate pump (price estimated)	100	1	100
		d) 6.9 gpm Ethylene Glycol (price from Appendix II)	286	1	286
		e) 15 gpm Ethylene Glycol (2 speed) (price from Appendix II)	330	1	330
				TOTAL	$2715

APPENDIX I.H (Continued)

PUMPS AND MOTORS

KEY CODE	CONTRACTOR NAME	DESCRIPTION	PRICE PER UNIT	NUMBER OF UNITS PER SYSTEM	DELIVERED COST PER SYSTEM
H9	Franklin Institute	46.7 GPM of Dowtherm J, at 30'head Burks close-coupled centrifugal standard construction 374G 6 - 1-1/2 pump 3/4 pump HP, 1750 RPM motor	386	1	$386
H12	Clemson University	46.7 GPM of Exxon Marcol at 30'head Burkes close-coupled centrifugal standard construction 374G 6 - 1-1/2 pump 3/4 pump HP, 1750 RPM motor	386	1	386
H17	Desert Reclamation Industries	1500 GPM of well water at 100' head crane Deming vertical turbine pumping unit. 14" two-stage bore assembly. 100' of 10" column and 1-1/4" shaft. Surface discharge head SD10-10-16 1/2 50 HP, 1750 RPM motor with nonreversible rachet	8990	40	359,600

APPENDIX I.H (Continued)

PUMPS AND MOTORS

KEY CODE	CONTRACTOR NAME	DESCRIPTION	PRICE PER UNIT	NUMBER OF UNITS PER SYSTEM	DELIVERED COST PER SYSTEM
H18	Texas A & M University	a) 600 GPM of water at 25' head Paco end suction centrifugal type L4070-5, bronze fitted with seal 5 HP, 1750 RPM motor close-coupled unitype	779.00	1	779.00
		b) 250 GPM of water at 25' head Paco 2570-5, bronze fitted with seal 2 HP, 1750 RPM motor close-coupled unitype	544.00	1	544.00
		c) 650 GPM of well water at 150' head crane Deming vertical turbine pumping unit. 10" 4-stage bore assembly. 150' of 8" column with 1" shafting. Surface discharge head SD88 - 16½ 40 HP, 1750 RPM motor with non reversible rachet	8610.00	3	25,830.00
					27.163.00
H19	Desert Reclamation Industries	800 GPM of well water at 100' head crane Deming vertical turbine pumping unit. 10" 3-stage bore assembly. 100' of 8" column with 1" shafting Surface discharge head SD 88-12 30 HP, 1750 RPM motor with non reversible rachet	6340	2	12,680.00
					12,680.00

APPENDIX I.I

CONTROLS

KEY CODE	CONTRACTOR	DESCRIPTION	ITEM COST ($)	TOTAL ($) FOR SYSTEM
I1	EIC Corporation	1-1/3 hp contactor for 5 gpm methanol pump	40	40
		1-30 gpm contactor for 150 gpm glycol pump	56	56
		3-15 hp starters for blowers	116	348
		8-2 1/2" Solenoid valves	175	1400
		2- 1/2" motorized ball valves	200	400
		2- 1/2" solenoid valves	35	70
		6- motorized dampers	110	660
		2- thermostats	81	162
		1- controller (25 elements) (5 in cabinet)		550
				3686
I2	EIC Corporation	1-1/3 hp contactor for 5 gpm methanol pump	40	40
		1-10 amp contactor for 24 gpm glycol pump	40	40
		3-1/3 hp contactor for blowers	40	120
		8-3/4" solenoid valves	40	320
		2-1/2" motorized ball valves	129	258
		2-1/2" solenoid valves	35	70
		6-motorized dampers	110	660
		2-thermostats	81	162
		1-controller (25 elements) (5 in cabinet)		550
				2220

APPENDIX I.I (Continued)

CONTROLS

KEY CODE	CONTRACTOR	DESCRIPTION	ITEM COST ($)	TOTAL ($) FOR SYSTEM
I3	Martin Marietta	3-20 amp contactors for pumps	49	147
		3-15 hp starters for blowers	116	348
		8-2 1/2" solenoid valves	175	1400
		2- 3" motorized ball valves	400	800
		1- expansion valve	50	50
		6- motorized dampers	110	660
		2-thermostats	81	162
		1-controller (24 elements) (6 in cabinets)		600
				4167
I4	Rocket Research	2-2 hp starters for 130 gpm H_2SO_4 pump (2 speed)		432
		1-15 hp starters for 30,770 CFM blower		116
		1-20 hp starter for 36870 CFM blower		116
		1-5 hp starter for 300 gpm pump (2 speed)		230
		1-2 hp starter for 119 gpm pump		45
		4-3 way 2" H_2SO_4 valves	675	2700
		4-3 way 2 1/2" ethylene glycol valves	220	880
		1-2 way 2" H_2SO_4 valve	450	450
		1-2 way 1/2" ethylene glycol valve	35	35
		2-thermostats	81	162
		1-4 hp starter for 150 gpm pump	55	55
		1-10 amp contactor	40	40
		4-motorized dampers	110	440
		1-controller (24 elements) (8 in cabinet)		720
				6421

APPENDIX I.I (Continued)

CONTROLS

KEY CODE	CONTRACTOR	DESCRIPTION	ITEM COST ($)	TOTAL ($) FOR SYSTEM
I5	Rocket Research	2-1/2 hp starters for 6.5 gpm H_2SO_4 pump (2 speed)		80
		1-3/4 hp starter for 1536 CFM blower		40
		1-1 hp starter for 2150 CFM blower		45
		1-3/4 hp starter for 15 gpm pump (2 speed)		216
		1-1/2 hp starter for 8.7 gpm pump		40
		1-1/2 hp starter for 6.9 gpm pump		40
		1-10 amp contactor		40
		4-3 way 1 1/2" H_2SO_4 valves	600	2400
		4-3 way 3/4" ethylene glycol valves	110	440
		1-2 way 1 1/2" H_2SO_4 valve		400
		1-2way 1/2" ethylene glycol valve		35
		4-motorized dampers	110	440
		2-thermostats	81	162
		1-controller (24 elements) (8 in cabinet)		720
				5098
I6	Rocket Research	2-2 hp starters for 130 gpm H_2SO_4 pump (2 speed)		432
		1-15 hp starter for 30,770 CFM blower		116
		1-20 hp starter for 36870 CFM blower		116
		1-5 hp starter for 300 gpm pump (2 speed)		230
		1-2 hp starter for 119 gpm pump		45
		4-3 way 2" H_2SO_4 valves	675	2700
		4-3 way 2 1/2" ethylene glycol valves	220	880
		1-2 way 2" H_2SO_4 valve	450	450
		1-2 way 1/2" ethylene glycol valve	35	35
		2-thermostats	81	162
		1-4 hp starter for 150 gpm pump	55	55
		1-10 amp contactor	40	40
		4-motorized dampers	110	440
		1-controller (24 elements) (8 in cabinet)		720
				6421

APPENDIX I.I (Continued)

CONTROLS

KEY CODE	CONTRACTOR	DESCRIPTION	ITEM COST ($)	TOTAL ($) FOR SYSTEM
I7	Rocket Research	2-1/2 hp starters for 6.5 gpm H_2SO_4 pump (2 speed)		80
		1-3/4 hp starter for 1536 CFM blower		40
		1-1 hp starter for 2150 CFM blower		45
		1-3/4 hp starter for 15 gpm pump (2 speed)		216
		1-1/2 hp starter for 8.7 gpm pump		40
		1-1/2 hp starter for 6.9 gpm pump		40
		1-10 amp contactor		40
		4-3 way 1 1/2" H_2SO_4 valves	600	2400
		4-3 way 3/4" ethylene glycol valves	110	440
		1-2 way 1 1/2" H_2SO_4 valve		400
		1-2 way 1/2" ethylene glycol valve		35
		4-motorized dampers	110	440
		2-thermostats	81	162
		1-controller (24 elements) (8 in cabinet)		720
				5098

APPENDIX I.I (Continued)

CONTROLS

KEY CODE	CONTRACTOR	DESCRIPTION	ITEM COST ($)	TOTAL ($) FOR SYSTEM
I8	University of Delaware	2- thermostats @ $35 ea.	70	-
I9	Franklin Institute	1-3/4 hp contactor for 46.7 gpm pump	40	-
		1-pressure switch	10	-
		1-thermostat	35	-
		1-controller (3 elements) (1 in cabinet)	90	175
I10	Dow Chemical	2- thermostats @ $35 ea (no cabinet)	70	70
I11	Dow Chemical	2- thermostats @ $35 ea (no cabinet)	70	70
I12	Clemson University	1-1 hp contactor for 50 gpm pump	40	-
		1- thermostat	35	-
		1- controller (2 elements) (1 in cabinet)	105	180
I13	University of Delaware	2- thermostats (no cabinet)	70	70
I14	Monsanto Research	1- thermostat (no cabinet)	35	35
I17	Desert Reclamation Inc.	40*-50 hp starters for 1500 gpm pumps @ 420 ea	16800	-
		160-8" motorized ball valves @ $1400 ea	224000	-
		160**-10 amp contactors @ 40 ea	6400	-
		1- controller (360 elements) (200 in cabinets)	33000	280200

* in banks of 4- $16,600 in controller cost
** in 4 cabinets -$6400 in controller cost

APPENDIX I.I (Continued)

CONTROLS

KEY CODE	CONTRACTOR	DESCRIPTION	ITEM COST ($)	TOTAL ($) FOR SYSTEM
I18	Texas A & M	1-5 hp starter for 600 gpm pumps	55	-
		1-2 hp starter for 250 gpm pump	46	-
		3-40 hp starters for 650 gpm pumps @ 190 ea	570	-
		2-10" PVC gate valves, motorized @ 1700 ea	3400	-
		2-8" PVC gate valves, motorized @ 1400 ea	2800	-
		4-6" PVC gate valves, motorized @ 800 ea	3200	-
		8-10 amp contactors @ 40 ea	320	-
		1- controller (21 elements) (13 in cabinets)	900	11291
I19	Desert Reclamation Inc.	2-30 hp starters for 800 gpm pumps @ 190 ea	380	-
		4-8" motorized gate valves @ 1400 ea	6400	-
		4-10 amp contactors @ 40 ea	160	
		1- controller (10 elements) (6 in cabinet)	500	7440

APPENDIX I.J.

INSTALLATION

KEY CODE	DESCRIPTION	COST PER SYSTEM
J1	Cost to install system on site. Included functions are: a) Build foundations for $CaCl_2$ tanks and methanol tank. b) Final assembly of $CaCl_2$ units c) Install three tanks, two pumps, three blowers, three heat exchangers d) Erect and hang air ducts e) Connect piping and electricals f) Charge system g) Transportation to site from contractor's place	$7345
J2	Cost to install system on site. Included functions are: a) Build foundations for $CaCl_2$ tanks and methanol tank. b) Final assembly of $CaCl_2$ units c) Install three tanks, two pumps, three blowers, three heat exchangers d) Erect and hang air ducts e) Connect piping and electricals f) Charge system g) Transportation to site from contractor's place	6391
J3	Cost to install system on site. Included functions are: a) Build foundations and install storage medium and ammonia tank b) Install three heat exchangers, three pumps, three blowers c) Erect and hang air ducts d) Connect piping and electricals e) Transportation from contractor's place to site	2559
J4	Cost to install system on site. Included functions are: a) Build foundations for conc. H_2SO_4 and dilute H_2SO_4 tanks b) Install H_2SO_4 tank c) Install water tank d) Install heat exchangers, pumps, and blowers e) Erect and hang ducts f) Connect piping and electricals g) Charge system h) Transportation to site from contractor's place	11,661

APPENDIX I.J

INSTALLATION

KEY CODE	DESCRIPTION	COST PER SYSTEM
J5	Cost to install system on site. Included functions are: a) Build foundations for conc. H_2SO_4 and dilute H_2SO_4 tanks b) Install H_2SO_4 tank c) Install water tank d) Install heat exchangers, pumps, and blowers e) Erect and hang ducts f) Connect piping and electricals g) Charge system h) Transportation to site from contractor's place	5369
J6	Cost to install system on site. Included functions are: a) Build foundations for conc. H_2SO_4 and dilute H_2SO_4 tanks b) Install H_2SO_4 tank c) Install water tank d) Install heat exchangers, pumps, and blowers e) Erect and hang ducts f) Connect piping and electricals g) Charge system h) Transportation to site from contractor's place	6685
J7	Cost to install system on site. Included functions are: a) Build foundations for conc. H_2SO_4 and dilute H_2SO_4 tanks b) Install H_2SO_4 tank c) Install water tank d) Install heat exchangers, pumps, and blowers e) Erect and hang ducts f) Connect piping and electricals g) Charge system h) Transportation to site from contractor's place	3859

APPENDIX I.J (Continued)

INSTALLATION

KEY CODE	DESCRIPTION	COST PER SYSTEM
J8	Cost to install system on site. a)Build foundation support b)Arrange chubs and racks c)Install plywood enclosure (double wall) d)Hook up input and output ducting e)Connect electricals f)Transportation to house from contractor's place	255
J9	Included in the cost are: a)Cost of assembling piping, evaporator and pump in shop b)Work done on site such as build foundation, install unit, hook up piping, charge system, connect electricals c)Transportation to house from contractor's place	322
J10	Cost to install system on site. a)Foundation support b)Install cans and the enclosure c)Hook up input and output ducting d)Connect electricals e)Transportation to house and into the basement	330
J11	Cost to install system on site: a)Foundation support b)Install cans and the enclosure c)Hook up input and output ducting d)Connect electricals e)Transportation to house and into the basement	$ 488
J12	Cost includes: a)Assemblies: pump, heat exchanger, expansion tank b)Foundation for the unit c)Install tank d)Hook up piping e)Connect electricals f)Charge system g)Transportation from contractor's place	322

APPENDIX I.J (Continued)

INSTALLATION

KEY CODE	DESCRIPTION	COST PER SYSTEM
J13	Cost to install system on site: a)Build foundation support b)Arrange chub and racks c)Install plywood enclosure (double wall) d)Hook up input and output ducting e)Connect electricals f)Transportation to house from contractor's place	330
J14	Cost to install system in residence: a)Install steel and expansion tank b)Foundation c)Connect piping and electricals d)Charge system e)Transportation from contractor's place to residence	254
J15	Lay block wall of 276 blocks Apply butyl adhesive bonding agent	625
J16	Lay block wall of 1000 blocks Apply type N mortar	2,074
J17	a)Drill 40 wells, 400 ft. deep 24" dia. b)Install filter and three pumps c)Machine trenching and backfill d)Connect electricals	3,156,343
J18	a)Drill 3 wells 150 ft. deep 12" dia. b)Install filter and three pumps c)Machine trenching and backfill d)Connect electricals	66,139
J19	a)Drill 2 wells, 400 ft. deep 24" dia. b)Install one heat exchanger and two pumps c)Machine trenching and backfill d)Connect electricals	$180,475

APPENDIX II

GENERALIZED COST DATA

APPENDIX II

GENERALIZED COST DATA

APPENDIX II.A PRICE AND PROCUREMENT CONSIDERATIONS FOR CHEMICALS USED IN HEAT STORAGE SYSTEMS

This section of the report deals with price and procurement considerations for the various chemicals used in selected heat storage systems. It begins with a general discussion of purchasing considerations and includes comments on the availability of the chemicals under consideration. Finally, a description of the approach used in estimating delivered costs for the heat storage chemicals is presented, in conjunction with a brief discussion of the importance of transportation cost to the delivered cost figures for certain chemicals.

1. General Procurement Considerations for Heat Storage Chemicals

The procurement process involves a series of decisions which begin with the choice of material to be used in a given process. Indeed, a major element of this study is the selection of a number of viable heat storage systems, based on their relative cost effectiveness. For many of the systems the chemical costs represent a significant portion of total cost and, therefore, have a marked impact on system viability. Selection of an effective heat storage system based on chemical materials which are readily available at low cost is an important objective.

Once the choice of material is made on the basis of expected chemical availability and heat storage cost effectiveness, the next decision is whether to make or buy the material. For nearly every system considered the estimated chemical requirements are small relative to U.S. production of these chemicals. This suggests that manufacturing the chemicals would not be practical, with the possible exception of forming a hydrated salt from anhydrous material.

Once the decision has been made to purchase the chemicals required, several additional considerations arise relating to the choice of by-product or virgin material and to the choice of individual suppliers. The first choice will be made on the basis of both by-product availability and the purity requirements of the heat storage system. The choice of supplier may involve a number of considerations including a) the possibility of dealing directly with the producer rather than with middlemen, b) the issue of having alternate sources of supply and therefore, splitting the order among several purchasers and, finally, c) geographic considerations in which preference may be given to either a local supplier or to suppliers who are in a position to minimize transportation costs.

To summarize, there are four basic considerations which should go into the purchasing decision:

- Current and future availability of the chemical,
- Purity or quality requirements for the intended use,
- Technical service requirement and availability, and
- Delivered price of the chemical.

Although the delivered price of the chemical has a significant impact on the economic viability of the heat storage system, consideration of price alone assumes that sufficient quantities of the chemical will be available in the required purity and that the amounts required will be small enough, compared to total demand, to have no effect on price. As will be discussed, this is not always the case.

2. Product Availability

Based on estimated sales volumes for the individual heat storage systems as well as the material requirements for these systems, estimates were prepared of the potential annual demand for the heat storage chemicals considered. Where information on U.S. production of the individual chemicals was available, heat storage demand was compared with production to arrive at an estimate of the share of U.S. output potentially required for heat storage applications. The results of this analysis are shown in Table II.A-1. For purposes of this analysis, heat storage demand levels of less than 5% of U.S. production were considered to be inconsequential. This eliminated from consideration all chemicals for which information was available except for sodium thiosulfate, trimethylamine, and calcium chloride.

Based on the sales estimates for the Clemson University and Franklin Institute systems, demand for sodium thiosulfate and trimethylamine will exceed recent production figures for these chemicals by 219% and 29%, respectively. The relatively limited availability of these chemicals may thus present a problem.

In another example, based on a sales estimate of 4,000 units per year, the EIC Corporation heat storage system would require 160,000 tons of anhydrous calcium chloride annually. Sales of the system would also translate to an annual requirement of about 100,000 tons of methanol. These quantities represent 13% and 3%, respectively, of 1976 U.S. production of these chemicals. While the 3% figure for methanol may be worth noting, this level of additional demand would be unlikely to significantly disrupt methanol markets. On the other hand, in the case of calcium chloride, incremental demand amounting to about 13% of current production would be likely to force supply and demand out of balance and drive product prices higher.

TABLE II.A-1

TOTAL CHEMICAL DEMAND FOR INDIVIDUAL STORAGE SYSTEMS

System	Estimated System Sales (units/yr.)	Chemicals Used	Estimated Total Chemical Demand (1,000 tons)	Estimated 1976 Production Volume[a] (1,000 tons)	Demand as a Percent of Production
EIC Corporation	4,000	CH_3OH	100	3,121	3
		$CaCl_2$	160	1,200	13
Martin Marietta	36,000	$MgCl_2$	9	n.a.	M
		$CaCl_2$	11	1,200	1
		NH_3	17	16,464	0.1
EIC Corporation	6,000	CH_3OH	53	3,121	2
		$CaCl_2$	84	1,200	7
Rocket Research Corp.	6,000	H_2SO_4	33	33,001	0.1
		H_2SO_4	17	33,001	.05
Martin Marietta	6,000	$MgCl_2$	30	n.a.	M
		$CaCl_2$	37	1,200	3
		NH_3	57	16,464	0.3
Chemical Energy Specialists	36,000	$MgCl_2 \cdot 4H_2O$	23 (13 t.t. anhyd.)	n.a.	M
Rocket Research Corp.	1,000	H_2SO_4	275	33,001	1
University of Delaware	90,000	$Na_2SO_4 \cdot 10H_2O$	95 (42 t.t. anhyd.)	1,260	3
		Borax	4	900	0.4
		Min-U-Gel	8	n.a.	U
		$NaCl_2$	14	42,000	0.03
		kcl	15	315[b]	.5

TABLE II.A-1 (Continued)

TOTAL CHEMICAL DEMAND FOR INDIVIDUAL STORAGE SYSTEMS

System	Estimated System Sales (units/yr.)	Chemicals Used	Estimated Total Chemical Demand (1,000 tons)	Estimated 1976 Production Volume[a] (1,000 tons)	Demand as a Percent of Production
Brookhaven National Lab.	30×10^6 blocks	$CaCl_2 \cdot 6H_2O$	94 (47 t.t. anhyd.)	1,200	4

Key

a. Production reported on anhydrous basis unless otherwise indicated.
b. 1974 production estimate.
c. 1975 production estimate.
L. Unknown; supply likely to represent a constraint.
M. Unknown; supply may represent a constraint.
U. Unknown; supply unlikely to represent a constraint.

Source: Arthur D. Little, Inc., estimates based on published data.

TABLE II.A-1 (Continued)

TOTAL CHEMICAL DEMAND FOR INDIVIDUAL STORAGE SYSTEMS

System	Estimated System Sales (units/yr.)	Chemicals Used	Estimated Total Chemical Demand (1,000 tons)	Estimated 1976 Production Volume[a] (1,000 tons)	Demand as a Percent of Production
Franklin Institute	90,000	$N(CH_3)_3$	18	14[c]	129
Dow Chemical	40,000	$Mg(NO_3)_2 \cdot 6H_2O$	66 (29 t.t. anhyd.)	n.a.	M
Dow Chemical	36,000	$Mg(NO_3)_2 \cdot 6H_2O$	59 (26 t.t. anhyd.)	n.a.	M
		NH_4NO_3	59	7,185	1
Clemson University	36,000	$Na_2S_2O_3 \cdot 5H_2O$	80 (51 t.t. anhyd.)	16[d]	319
University of Delaware	36,000	Na_2SO_4	32	1,260	3
		Borax	2	900	0.2
		Min-U-Gel	6	n.a.	U
		H_2O	32	-	U
Monsanto Research Corp.	1,000	h.d.p.e.	1	1,560	.06
		Ethylene glycol	1	1,680	.06
Suntek Research Corp.	30×10^6 blocks	Pumice Cement	240	-	U
		$CaCl_2 \cdot 6H_2O$	180 (90 t.t. anhyd.)	1,200	8
		$BaCl_2 \cdot 6H_2O$	5 (3 t.t. anhyd.)	n.a.	L
		Urethane/Coal Tar	6	-	U

Although of lesser consequence, the alternative EIC Corporation system for which sales of 6,000 units per year are anticipated would have methanol and calcium chloride requirements representing 2% and 7%, respectively, of 1976 U.S. production of these chemicals. Here again, the 2% is hardly worth noting but the 7% is cause for some concern.

Finally, there are several chemicals for which production volume is not available and where supply may be a constraint: magnesium nitrate, magnesium chloride, and barium chloride.

In examining the likely longer-term availability of the various heat storage chemicals considered, no severe shortages (other than those noted above) are expected in the foreseeable future. On the other hand, several of the chemicals, including calcium chloride, sodium sulfate, and sodium chloride may be produced as co-products or by-products of other operations and, if quality is acceptable, may be available at prices below those for virgin material. A slower general rate of price increase for these chemicals is the one discernable price trend one sees here.

3. Estimated Delivered Cost for Heat Storage Chemicals

As an important input to the total cost of the heat storage systems under study, estimates of delivered prices for the chemical materials were prepared (see Table II.A-2). In preparing these estimates, certain assumptions were made, including delivery of the chemicals to a Midwest U.S. location, and transportation costs of 5¢ per gallon or 1¢ per pound for products sold on an F.O.B. basis (which was the case for most of the chemicals). It was also assumed that hydrated salts of such chemicals as calcium chloride and magnesium chloride were prepared on-site in order to realize significant transportation cost savings. Although preparation of the desired hydrated form may be difficult in some cases, it was assumed that this step could be carried out with relatively simple equipment for a fraction of a cent per pound.

The delivered cost of the chemicals varied widely from a low of 1.3¢ per pound for sodium sulfate decahydrate up to 29¢ per pound for high-density polyethylene resin, and 80¢ per pound for the urethane/coal tar sealant which is called for in the Suntek Research Corporation system.

The product prices were prepared on the basis of published list prices and direct telephone contact with producing companies. Companies contacted included Ashland Chemical Co., E.I. Du Pont de Nemours & Co. (Inc.), Tenneco, Hercules, and McKesson Chemical Co.

Transportation costs become relatively significant for those products with low values per unit weight. Those chemicals for which estimated transportation costs account for 20% or more of delivered cost included anhydrous calcium chloride (20%), sulfuric acid (23%), Min-U-Gel (33%) and sodium chloride (33%).

TABLE II.A-2

SUMMARY OF CHEMICAL PRICES USED IN SYSTEM COST ESTIMATES

(cents/lb unless noted)

Chemical	Grade	Delivered Price[a]
Ammonia, Anhydrous	-	6
Ammonium Chloride	"fine"	14
Ammonium Nitrate	"fertilizer"	6
Barium Chloride, Hexahydrate	-	14
Calcium Chloride, Anhydrous	94-97%	5
Calcium Chloride, Hexahydrate	-	2.5
Ethylene Glycol	"industrial"	25
High-Density Polyethylene	-	29
Magnesium Chloride, Anhydrous	92%	15
Magnesium Chloride, Tetrahydrate	-	9
Magnesium Nitrate, Hexahydrate	-	16
Methanol	99%	54¢/gallon
Methanol	91%	49¢/gallon
Min-U-Gel	-	3
Potassium Chloride	"chemical"	3
Sodium Borate (Borax)	"technical"	20
Sodium Chloride	"chemical"	3
Sodium Sulfate, Decahydrate	-	1.3
Sodium Thiosulfate, Pentahydrate	-	12
Sulfuric Acid	93%	3
Sulfuric Acid	10%	0.5
Trimethylamine	100%	31.5
Urethane/Coal Tar Sealant	-	80-95
Exxon Marcol 72	-	$1.25/gallon

a. Assumes delivery to midwest location; hydrated salts produced on-site from anhydrous material.

Source: Arthur D. Little, Inc., estimates based on published data and industry contacts.

General sources of information on chemical suppliers and producers are the "OPD Chemical Buyers' Directory," the "Directory of Chemical Producers," and the "Chemical Week Buyers' Guide Issue." These sources are listed in Table II.A-3. Direct contact with major suppliers is generally the best approach to developing data on price and availability.

TABLE II.A-3

SOURCES OF INFORMATION ON CHEMICAL SUPPLIERS

"OPD Chemical Buyers' Directory," Schnell Publishing Company, Inc., 100 Church Street, New York, New York 10007

"Directory of Chemical Producers," Stanford Research Institute, Menlo Park, California 94025

"_Chemical Week_, Buyers' Guide Issue," McGraw-Hill Inc., 1221 Avenue of the Americas, New York, New York 10020

APPENDIX II.B CONTAINERS

1. Nonstandard Items

Container costs for special fabrications must be obtained either by getting quotes from vendors or by making a detailed list of materials and assembly operations, obtaining material prices and estimating assembly labor required. The assembly labor is then priced to include overhead and profit. Different costs/hr are used depending on the degree of automation likely. We have used standard crews from the "1978 Means Cost Data" handbook when applicable or the following:

- $20/hr Standard Factory Labor
- $25/hr Intermediate volume production equipment
- $30/hr Sophisticated production equipment

2. Tanks

Many systems utilize various types of tanks. Figures II.B-1 through II.B-7 present cost data for a range of sizes and types.

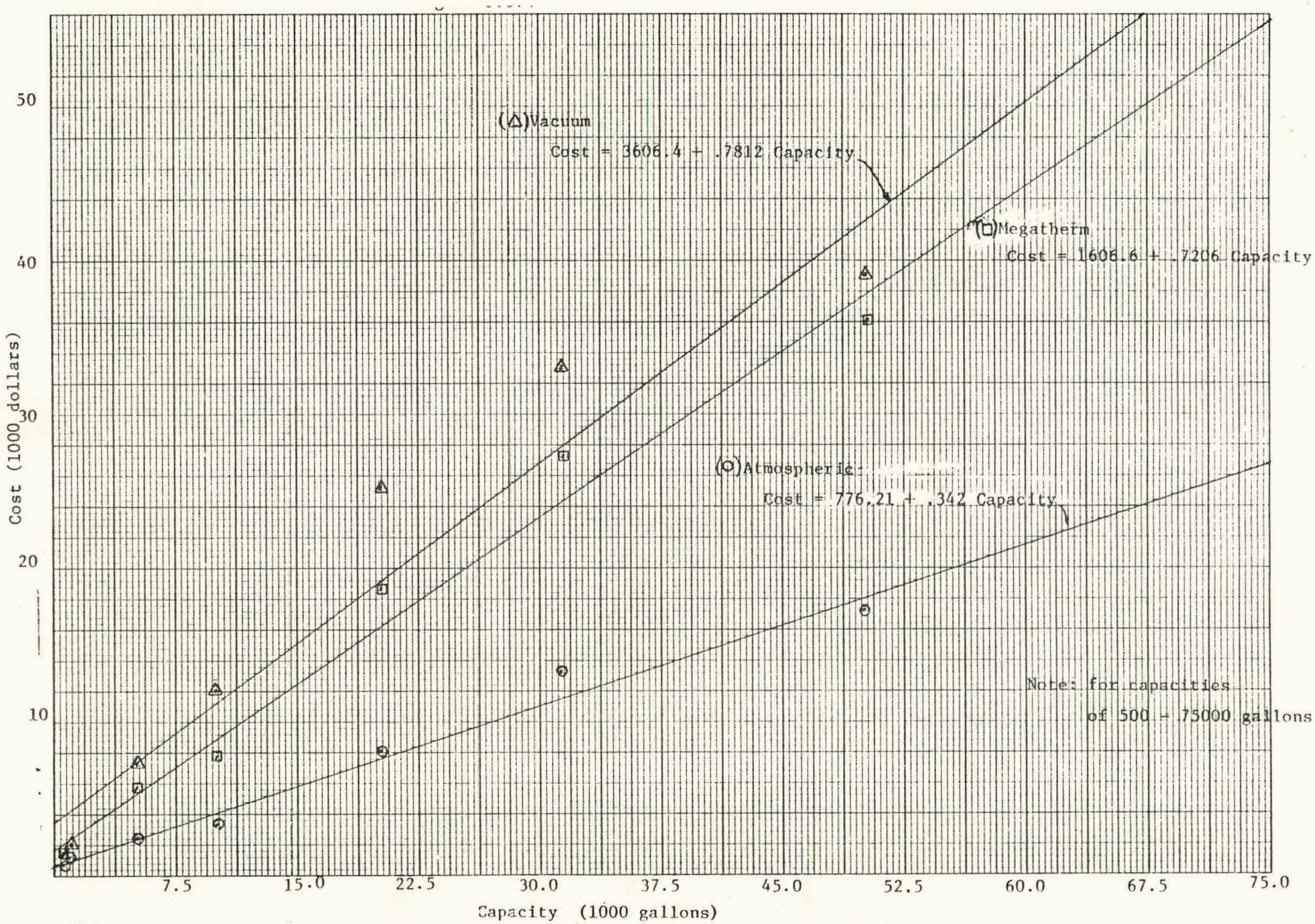


FIGURE II.B-1 DELIVERED COST OF STEEL TANKS

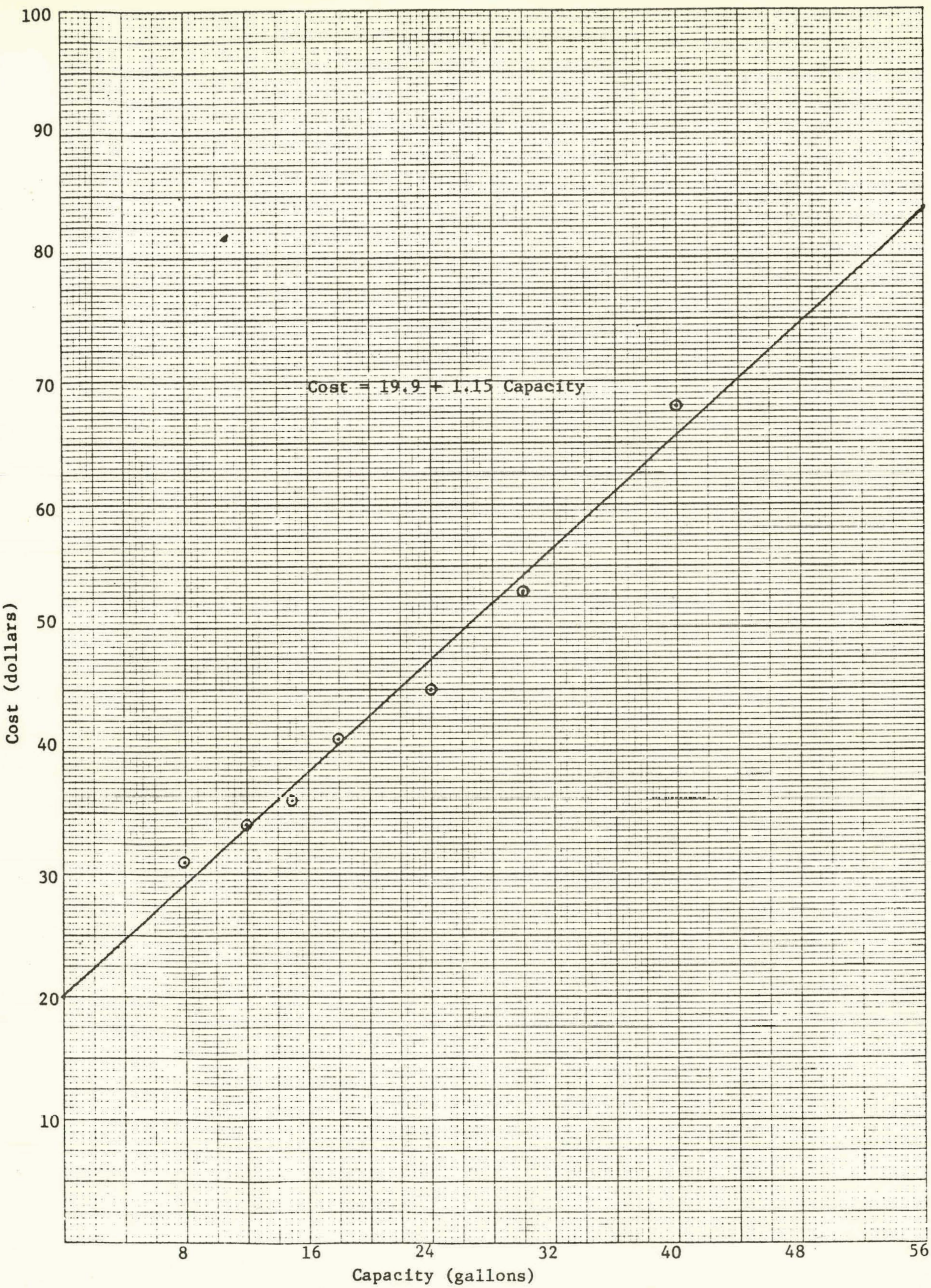


FIGURE II.B-2 DELIVERED COST OF STEEL EXPANSION TANKS

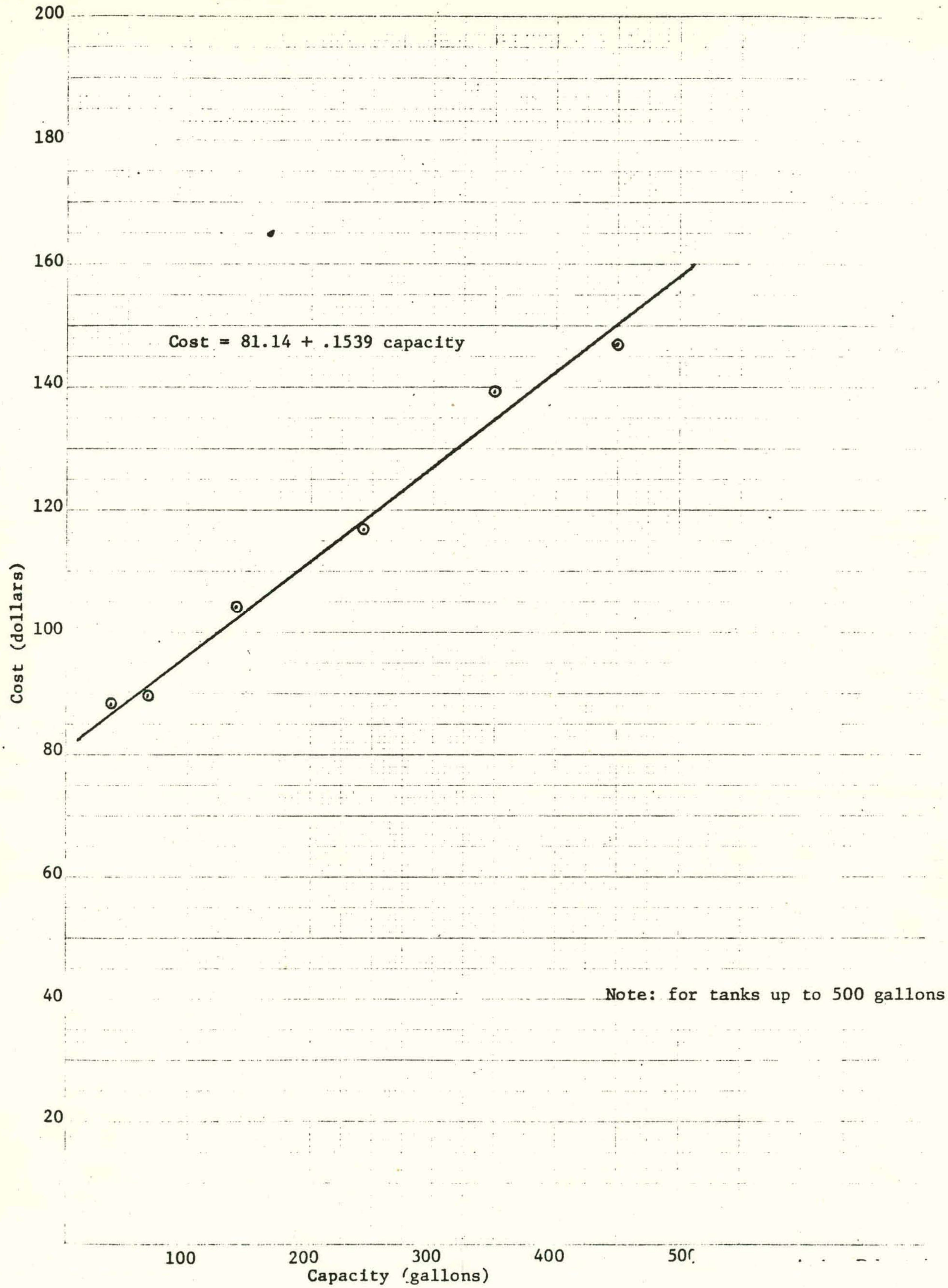


FIGURE II.B-3 DELIVERED COST OF UNPRESSURIZED AND UNLINED STEEL TANKS

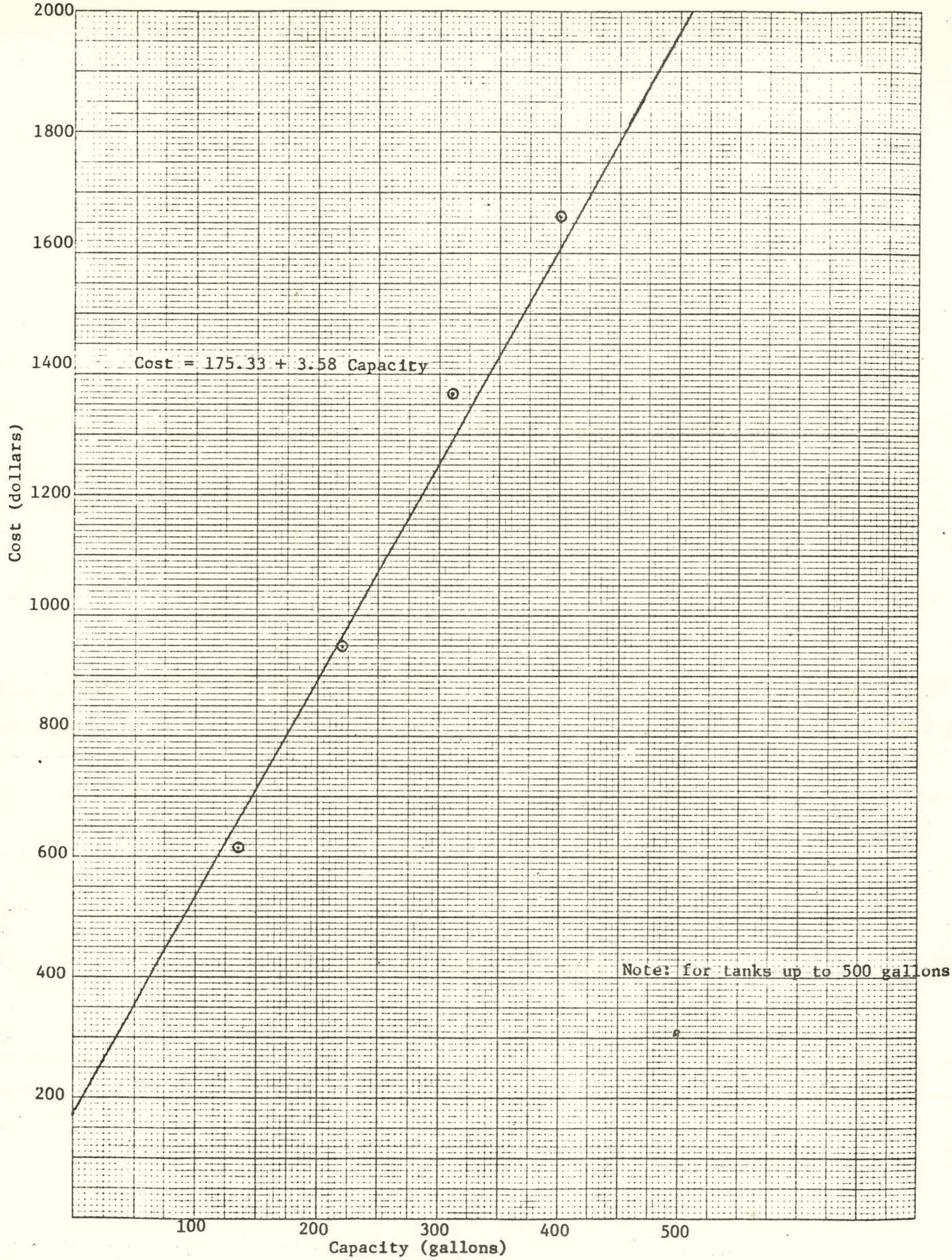


FIGURE II.B-4 COST OF PRESSURIZED STEEL TANKS

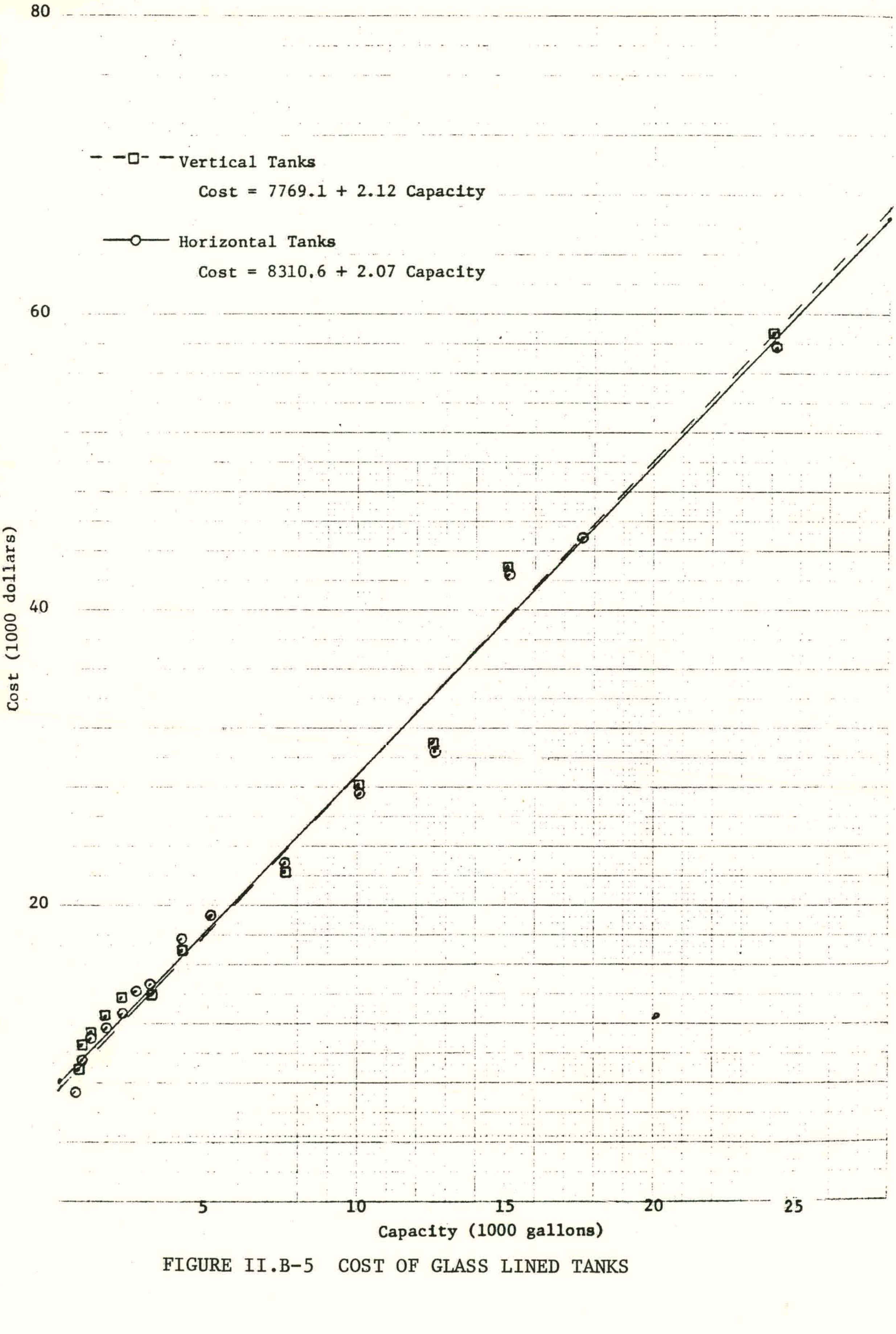


FIGURE II.B-5 COST OF GLASS LINED TANKS

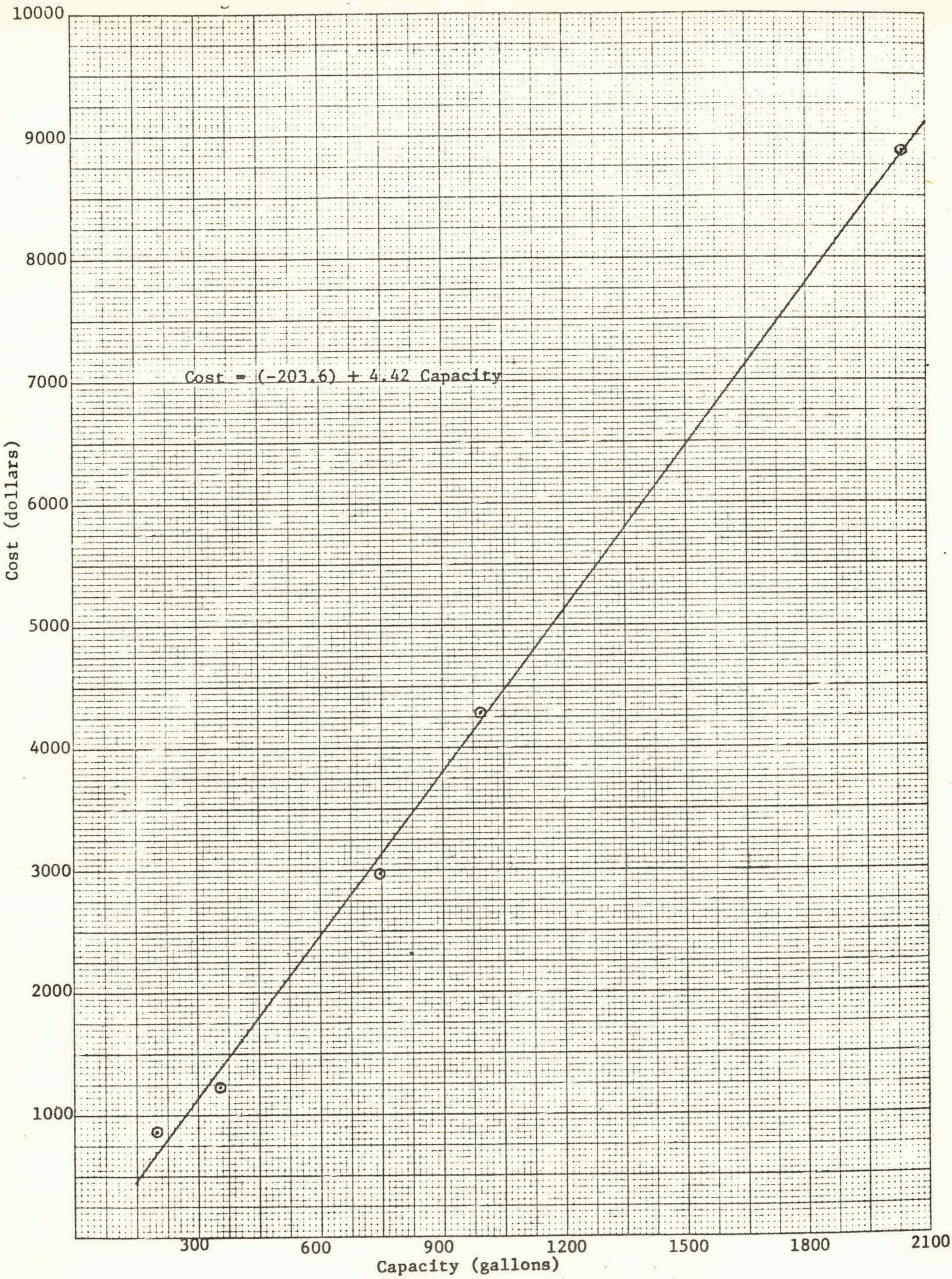


FIGURE II.B-6 COST OF A.O. SMITH GLASS LINED TANKS

(costs include foundation slab, sides and metal top, installed without pipes or pumps)

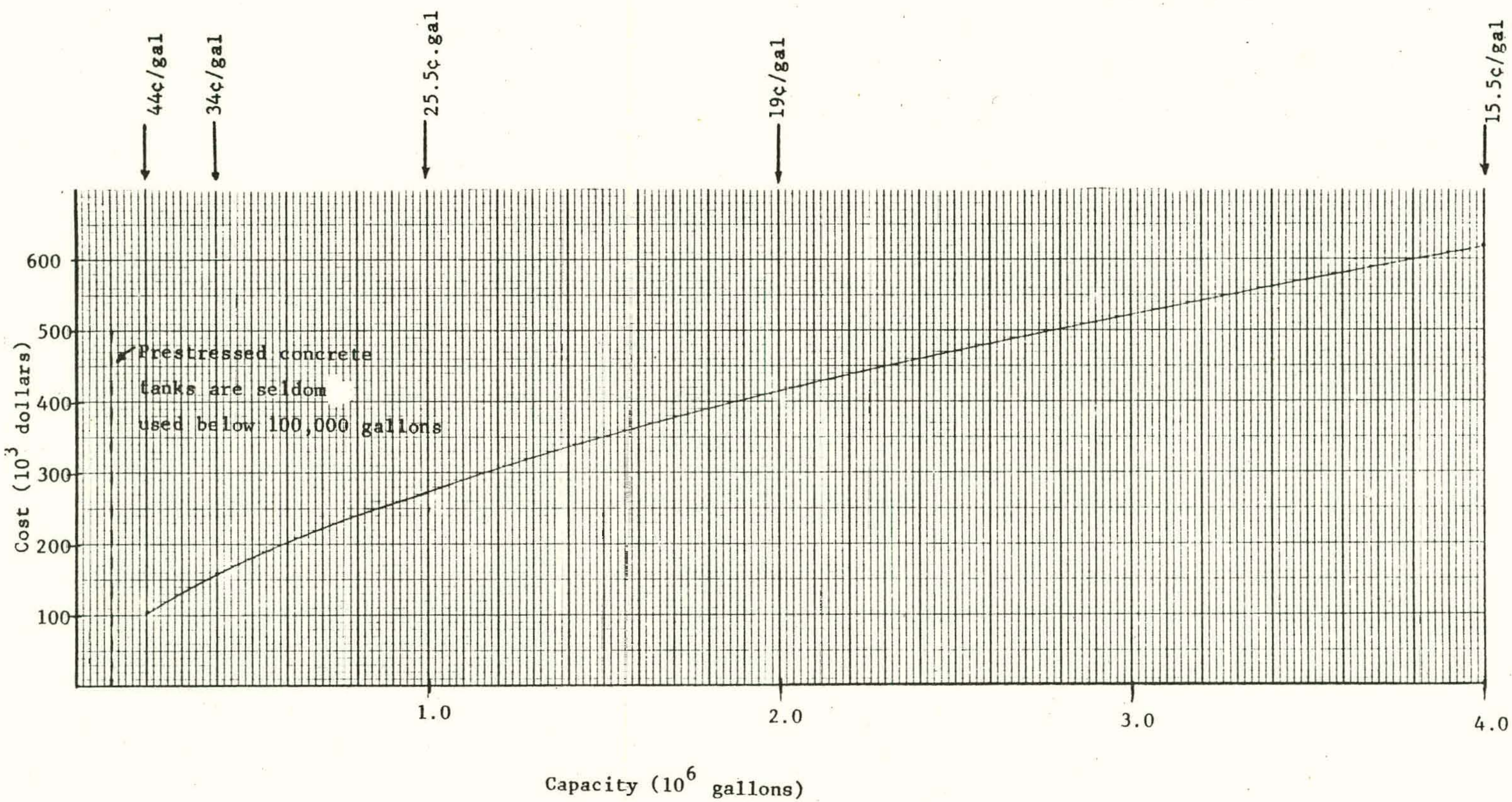


FIGURE II.B-7 PRESTRESSED CONCRETE TANK FOR LARGE VOLUME WATER STORAGE

3. Installation of Underground Tanks

Estimates of the installation costs of underground tanks were made for three different tank sizes. A graph showing the installed cost versus tank size is shown in Figures II.B-8. These installation costs assume that a hole would be excavated for the tank, the bottom would be prepared for the tank, the tank installed, and the hole back filled and compacted. The estimates were made using the Means Cost Data book to estimate the cost of excavating an amount of material based on the size of the tank for each tank utilizing trucks to carry the dirt and a clam shell to dig the holes. Standard labor rates were used which include typical contractor overhead and profit for an installation of this kind.

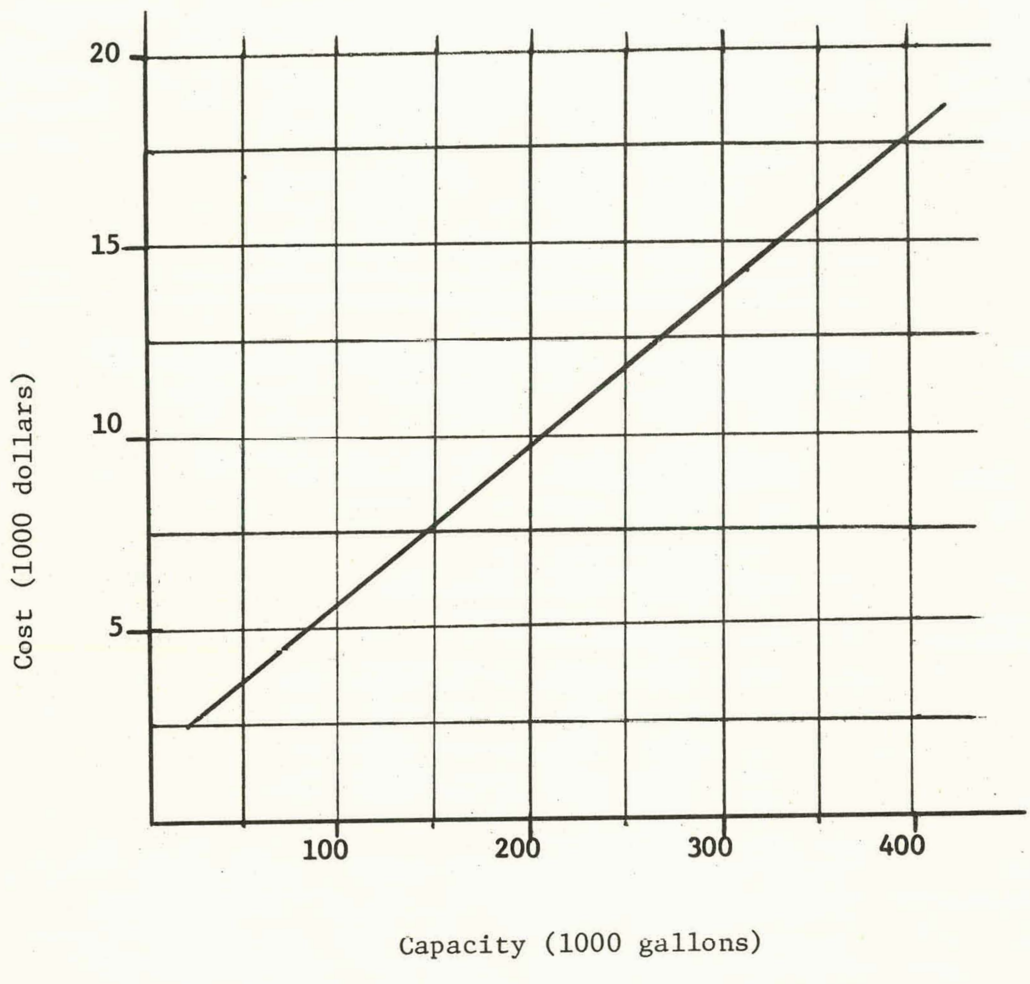


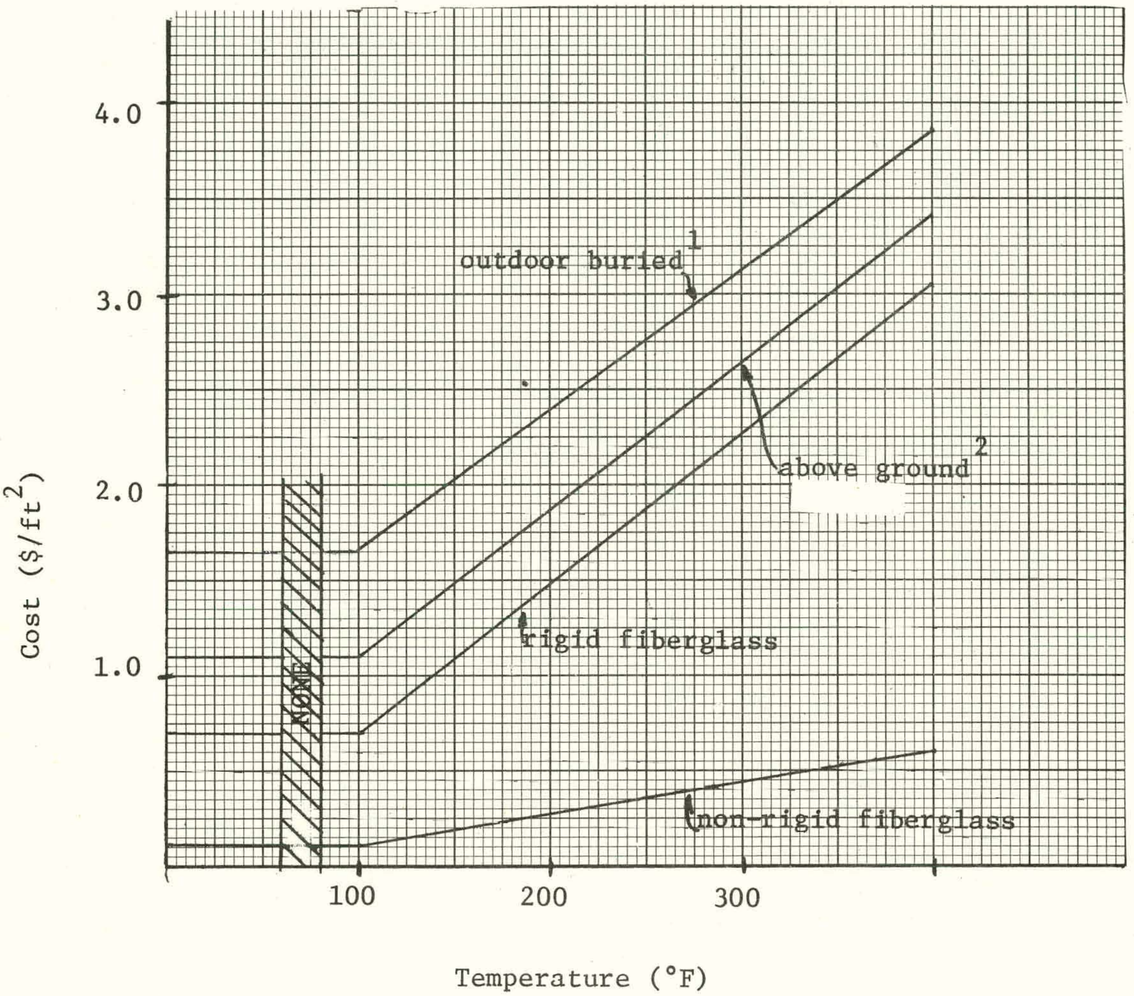
Figure II.B-8 Cost to Install Tanks Under Ground

APPENDIX II.C INSULATION

In order to estimate the cost of insulation in different types of storage devices, relationships have been developed between the cost per square foot of insulation and the temperature of the storage system. These relationships are based on an assumed standby loss rate. Figure II.C-1 shows these relationships for diurnal storage systems. For this comparison a value of 14 Btu/hour / ft^2 loss was selected as a standard rate. This value is the loss rate suggested in the new standard for water heaters. Four different curves are presented in Figure II-C.1. Non rigid and rigid fiberglass have been selected as the standard insulation on indoor applications. This insulation is good for a temperature up to approximately 400°F. Above this temperature composites must be used, and the cost per sq. ft. would increase somewhat more rapidly. Insulation for outdoor tanks is based on the use of rigid polyurethane attached to the device and covered with a cementitious coating to provide sealing. The tanks that are below the ground are assumed to have a waterproof coating over the cementitious coating. The values of insulation cost per sq. ft. include not only the materials but also the time required for installation and normal contractor overhead and profit.

In order to use this curve when costing a specific system, the surface area of the container being insulated is calculated based on its dimensions. Next, the maximum temperature of the storage device is estimated. Finally, the appropriate curve in the figure is selected in order to find the cost per unit area for insulation which corresponds to the storage temperature. For indoor tanks the surface area used should include the entire tanks container surface including top and bottom. For outdoor tanks above the ground only the surface area not in contact with the ground should be used because during diurnal cycles, the heat loss through the bottom is negligible compared to storage capacity of the device. Buried tanks do not need to be insulated for diurnal storage unless part of the tank is at or very close to the surface. In this case that portion of the tank within five feet of the surface should be insulated utilizing the curve shown for buried tanks.

For seasonal storage the insulation cost depends on whether the application is for heating or cooling. In the case of heating, an insulation value of R-30 is used for the tank. For temperatures normally encountered in this type of application, heat losses of 2 Btu per hr. per ft^2 for tank surfaces above ground and 1 Btu per hr. ft^2 for tanks below ground represent reasonable mean values. In treating seasonal storage the actual size of the storage tank should be scaled up to allow for this loss rate and the period of time over which the energy is to be stored. The costs associated with above ground and below ground installations on a per square ft basis are shown in Table II.C-1.



1 includes cementitious coating and waterproofing

2 includes cementitious coating

Notes:
- costs include installation based on 14 Btu/hr ft^2 loss
- system size may need to be scaled 5-10% larger to allow for losses

Figure II.C-1 Insulation for Diurnal Storage

Cooling applications for seasonal storage should use an insulation value of R-18 and the system should be scaled to allow for heat loss of .5 Btu's per hr per ft^2 for buried tanks and 1 Btu per hr per ft^2 for tanks above ground. When utilizing ice as the storage medium, .2 and .4 Btu's per hr ft^2 respectively should be used for chilled water systems. A different factor is utilized for this case because with an average ground temperature of 50^oF, the temperature difference for ice systems is somewhat larger than the average temperature if a chilled water storage system is utilized. Storage temperature differences were neglected for heating systems because for this case the differentials between typical storage temperatures and an earth temperature of 50^oF are large compared to differences in maximum storage temperature likely to be encountered in practice. Table II.A-1 also presents cost factors to be utilized for insulation costs for seasonal storage cooling applications.

TABLE II.C-1

SEASONAL STORAGE INSULATION DATA

	Above Ground		Below Ground	
	Loss Rate $(Btu/hr\ ft^2)$	Cost $(\$/ft^2)$	Loss Rate $(Btu/hr\ ft^2)$	Cost $(\$/ft^2)$
Heating (R-30)	2	3.56	1	3.56
Cooling Ice (R-18)	1	2.75	.5	2.75
Cooling Chilled Water (R-18)	.4	2.75	.2	2.75

APPENDIX II.D HEAT EXCHANGERS

A generalized method for estimating the cost of different types of heat exchangers has been developed, based on the NTU heat exchanger design method. This method utilizes the effectiveness of the heat exchanger to obtain an estimate of transfer units and from this to calculate the heat exchanger surface area for the particular application. The effectiveness is based on the temperature differences across the heat exchanger. Once the area has been obtained an equation is used to calculate the cost of the desired heat exchanger. These equations are summarized in Table II.D-1.

The step-by-step procedure for obtaining the estimated heat exchanger cost is as follows:

- Specify the heat exchanger by utilizing reasonable temperature drops across both fluid streams based on desired temperature drops throughout the storage unit and balancing the heat flow thermodynamically. This is done by using the heat capacity of the two fluid streams, their flow rates and the temperature differences to obtain the desired heat exchange rate.

- Calculate the required effectiveness by dividing the temperature difference of the stream having the maximum temperature (ΔT_{max}) change by the overall temperature difference across the heat exchanger (ΔT_o). The overall temperature difference is defined as the difference between the two inlet temperatures as shown in Figure II.D-1. Next η is calculated by dividing the temperature drop across the stream having the minimum temperature drop (ΔT_{min}) by the temperature drop across the stream with the maximum temperature drop (ΔT_{max}). Using these two values, the number of transfer units for the particular design is obtained from Figure II.D-2.

- Calculate the area of the heat exchanger required to give the necessary heat transfer surface from the equation

$$A = \frac{N_{tu} C_{min}}{U}$$

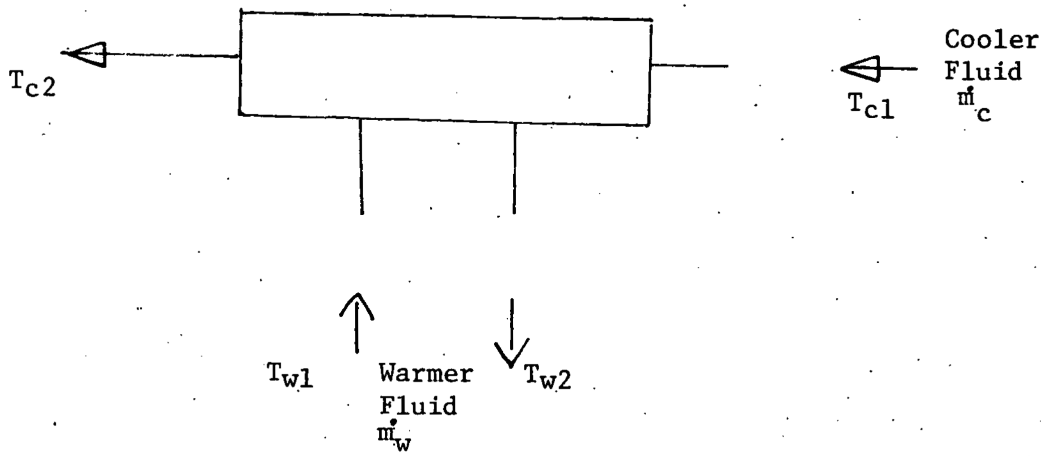
  where C_{min} is equal to the heat flow rate divided by the maximum temperature differential and U is the overall heat transfer coefficient which is obtained from Table II.D-2 for the appropriate case.

TABLE II.D-1

HEAT EXCHANGE COST EQUATIONS

TYPE	RANGE OF AREA (Ft^2)	COST ($)*
Standard Shell & Tube	$0 < A \leq 100$	$66A^{.55}$
Standard Shell & Tube	$100 < A < 200{,}000$	$17.1A^{.84}$
Glass Shell & Tube	A in jumps of 135 ft^2	5,500/unit
Finned Tube	$0 < A \leq 10{,}000$	175 + .545 A

* Note: Cost in 1978 dollars accurate to ± 10% for OEM purchases.



Nomenclature:

T_{c1}, T_{c2}: inlet and out temperatures of cooler fluid

T_{w1}, T_{w2}: inlet and outlet temperatures of warmer fluid

$\dot{m}_c$: mass flow rate of cooler fluid

$\dot{m}_w$: mass flow rate of warmer fluid

$T_o = T_{w1} - T_{c1}$

if

$$T_{w1} - T_{w2} < T_{c2} - T_{c1}$$

then $\Delta T_{max} = T_{c2} - T_{c1}$

$\Delta T_{min} = T_{w1} - T_{w2}$

if

$$T_{w1} - T_{w2} > T_{c2} - T_{c1}$$

then $\Delta T_{max} = T_{w1} - T_{w2}$

$\Delta T_{min} = T_{c1} - T_{c2}$

$$\varepsilon = \frac{\Delta T_{max}}{\Delta T_o}$$

$$\eta = \frac{\Delta T_{min}}{\Delta T_{max}}$$

$$(\dot{m}\ c_p)_{min} = \frac{Q}{\Delta T_{max}}$$

FIGURE II-D-1 NOMENCLATURE

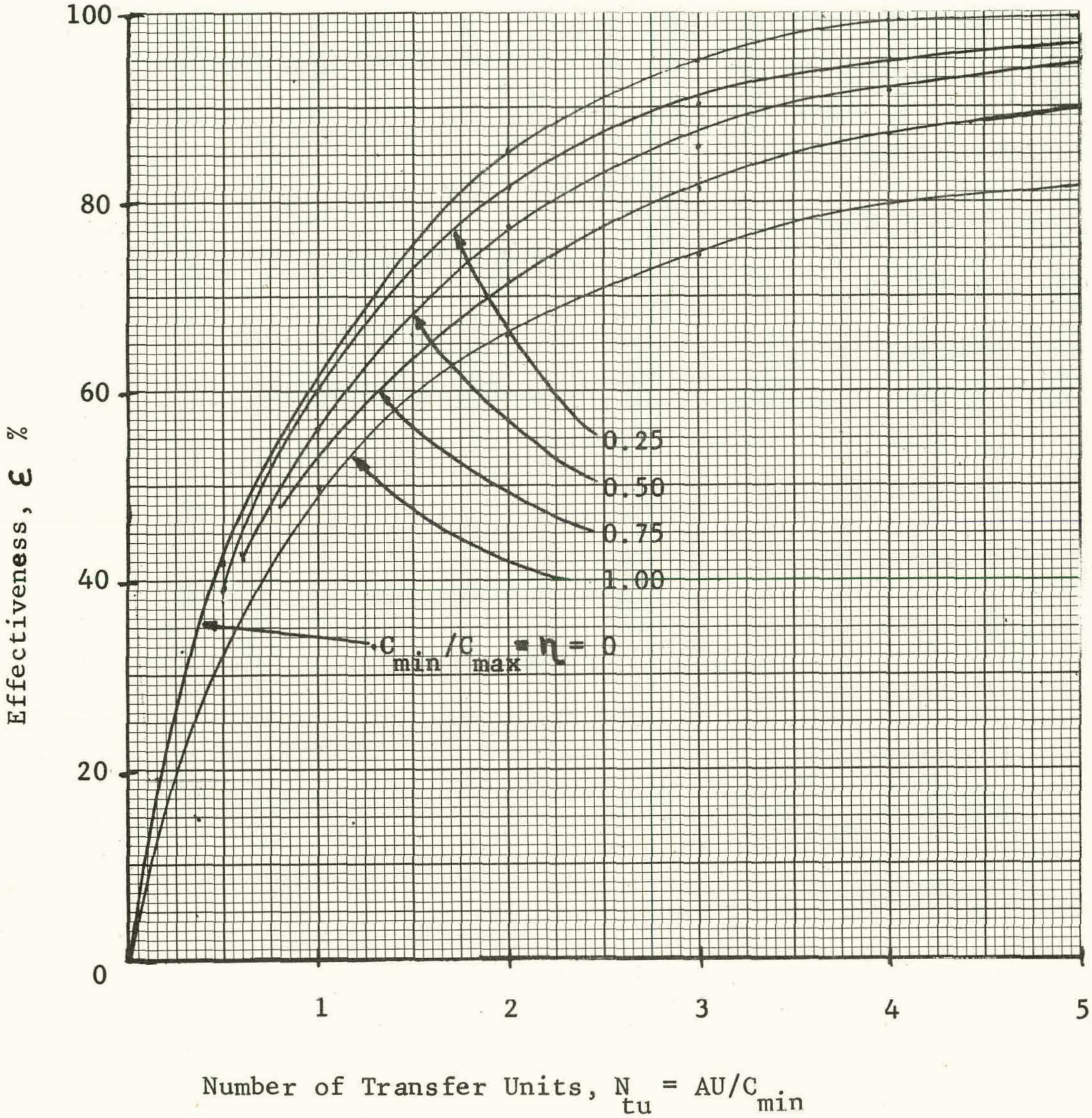


FIGURE II-D-2 TRANSFER UNITS AS A FUNCTION OF EFFECTIVENESS

TABLE II.D-2

CONDUCTANCE FOR VARIOUS HEAT EXCHANGER CONFIGURATIONS

TYPE OF HEAT EXCHANGER	FLUIDS	$U\left(\frac{Btu}{hr\ ft^2\ °F}\right)$
Standard Shell & Tube	Water-Ethylene Glycol	200
Standard Shell & Tube	Water - Heat Transfer Oils	30
Glass Shell & Tube	Concentrated H_2SO_4 - Ethylene Glycol	150
Standard Shell & Tube	Ethylene Glycol Evaporated or Condensed Fluid	160
Standard Shell & Tube	Water Condensed Water	250
Standard Finned Tube	Air- Ethylene Glycol	10
Standard Finned Tube	Air - Condensing Fluid	12
Standard Finned Tube	Air - Evaporating Fluid	20
Standard Shell & Tube	Vapor - Liquid	10

- Substitute the area calculated in this way into the appropriate equation from Table II.D-1 to obtain the estimated heat exchanger cost.

The relationships which relate cost to area have been derived for this program by obtaining quotes for heat exchangers which meet the design requirements of the different systems. These quotes were obtained from various sources. The fit of the actual data for heat exchangers to the curves given in Table II.D-1 provides an accuracy of plus or minus 10% of the estimated cost. These prices are for heat exchangers purchased only in large quantities.

APPENDIX II-E

HEAT TRANSFER FLUIDS

The pricing used for heat transfer fluids is described in Appendix II.A Heat Storage Material.

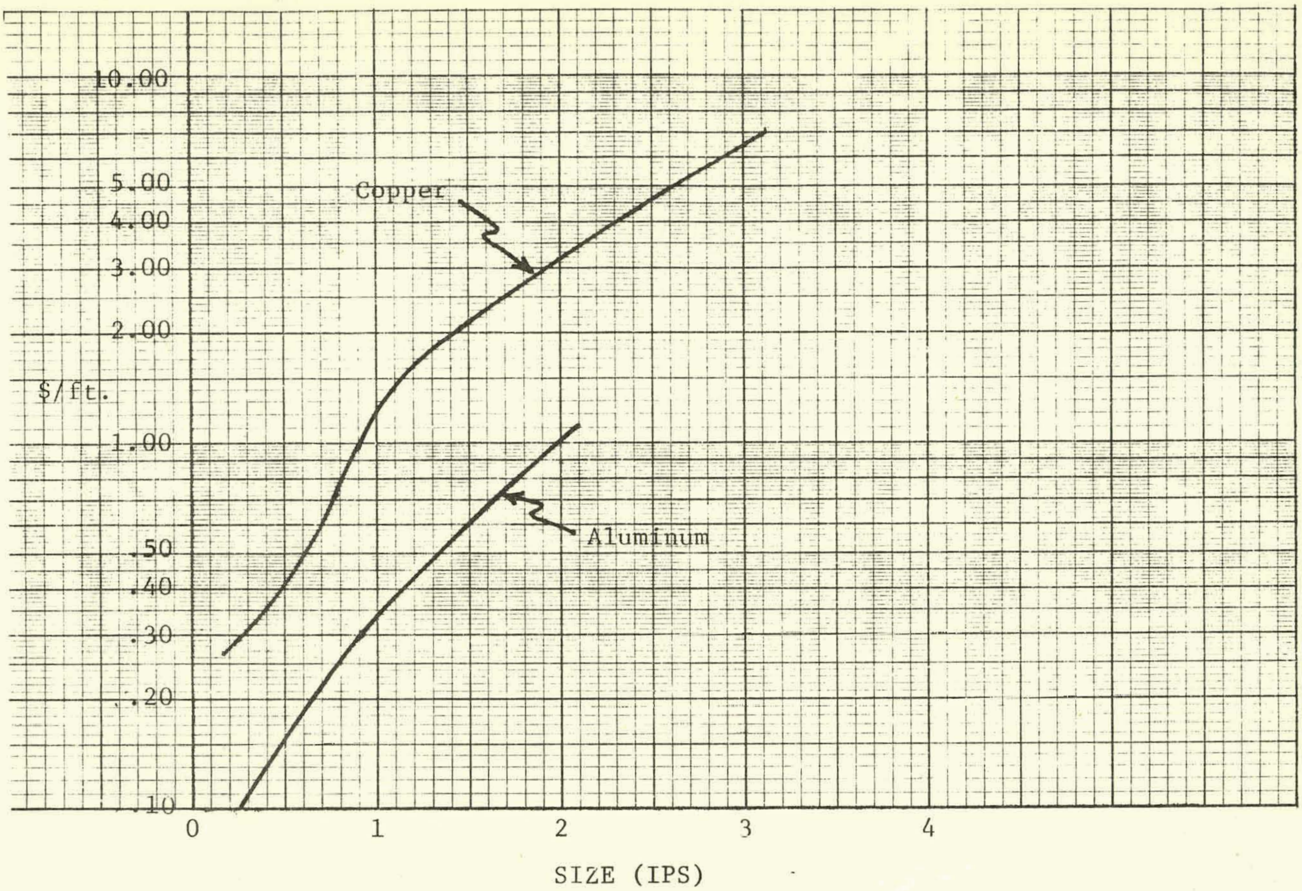
APPENDIX II.F

PIPING AND DUCTING

Cost curves relating pipe cost/ft to diameter for different materials are presented in Figure II.F-1. These are based on quotes from vendors for OEM quantities.

For costing ducts a figure of $.20/circumference inch/linear foot may be used to estimate the cost. This value was derived as shown in Table II.F-1 assuming 1 elbow every 25 feet. Use a maximum velocity of 100 feet/sec in commercial installations and 50 feet/sec for residential applications. A minimum duct size of 12" X 12" is practical.

Table II.F-2 describes the procedure for sizing pipes.



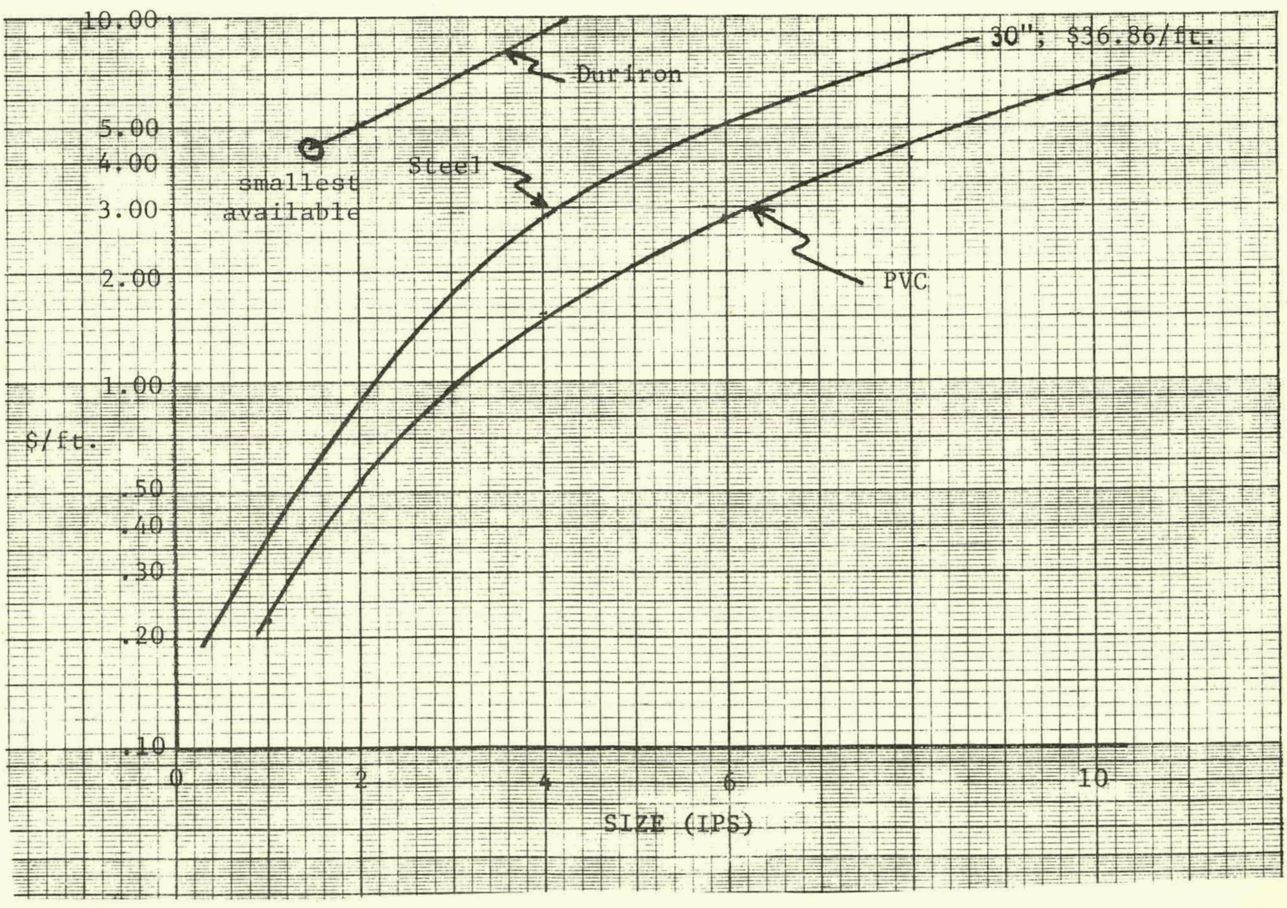


FIGURE II.F-1 PIPE COSTS

TABLE II. F-1

DUCTING COST ESTIMATE VALUE

SIZE	PERIMETER	$/25'	ELBOW ($)	TOTAL ($)	($/in ft)
24X28	104	450	54	504	.19
12X12	48	250	30	280	.23
28X39	134	550	66	616	.18
42X60	204	900	108	1008	.20
				Average	.20

TABLE II.F-2

DETERMINATION OF PIPE DIAMETERS

In order to determine the correct pipe diameter, one must specify the following:

flow rate

total pressure drop

total pipe length.

Using this information, one can determine the necessary diameter using Figures B-F-2 or B-F-3 depending on the flow rates involved. An example of the procedure employed is given below.

Problem: determine the required pipe diameter for the following set of conditions

Δh = 30 ft of H_2O (maximum)

flow rate = 70 gpm

pipe length = 90 ft

Method of Solution: calculate $\Delta h/1 = \frac{30 \text{ ft } H_2O}{90 \text{ ft pipe}} = .33 \text{ ft } H_2O/\text{ft pipe}$

on the abscissa of Figure II, F-2, locate the flow rate of 70 gpm; follow this line to the intersection of the calculated value of $\Delta h/1$ on the ordinate read pipe diameter from diagonal line to the right of the given point

Solution: 1 1/2" diameter pipe

In sizing piping for these analyses, we have used a standard pressure drop of 30 ft of water in all piping. This value has then been used as the basis for calculating pump and motor sizes in costing these items. In some residential applications pipe sizes will be large enough using 1/2" - 1" pipe to use 6 ft of water pressure drop. This will result in a lower pump cost. For larger systems with long pipe runs, the additional cost of the pipe offsets the higher pump cost so the 30 ft figure is more appropriate.

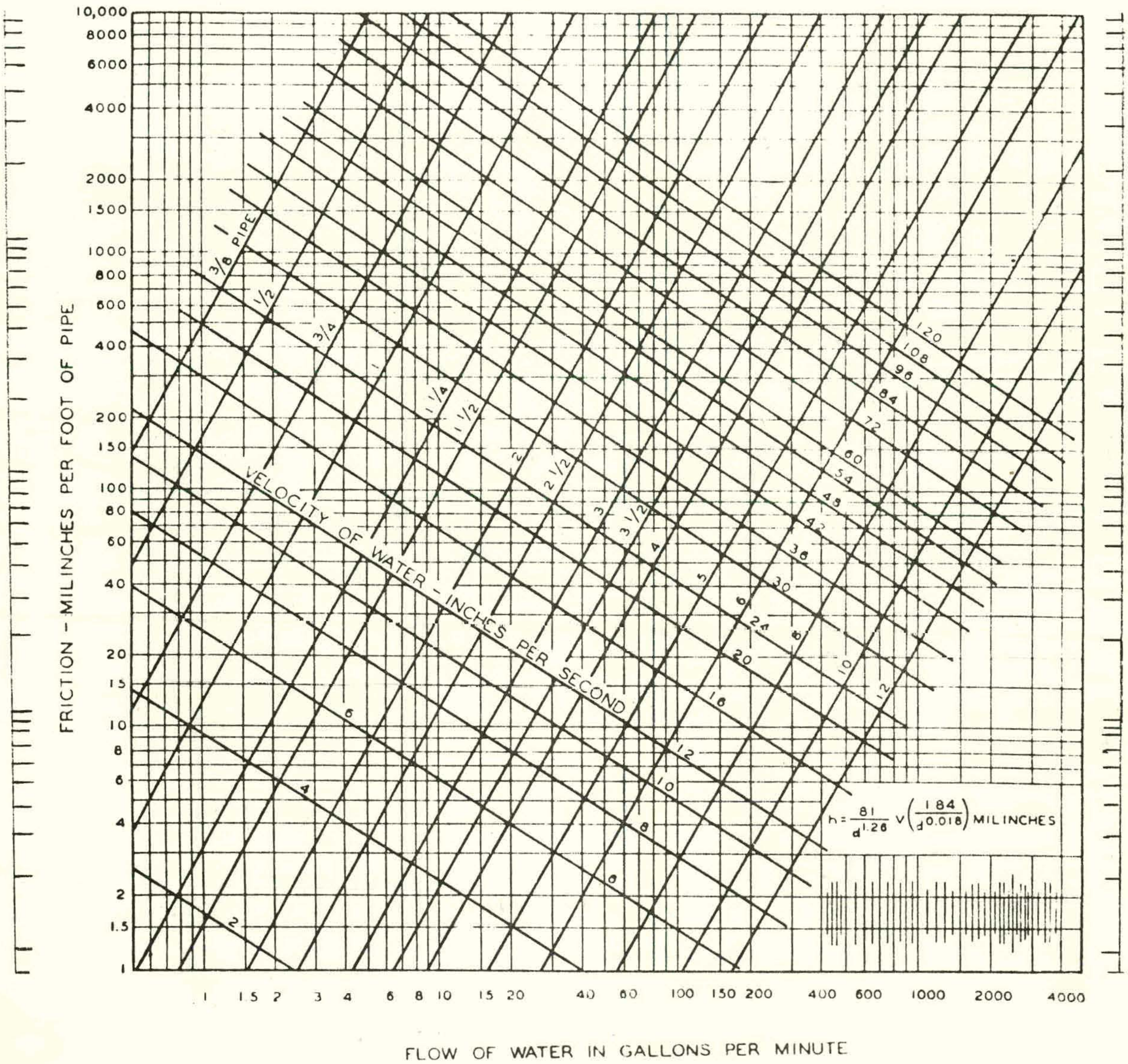


FIGURE II.F-2 PRESSURE DROPS AND PIPE DIAMETERS FOR SMALLER FLOW RATES

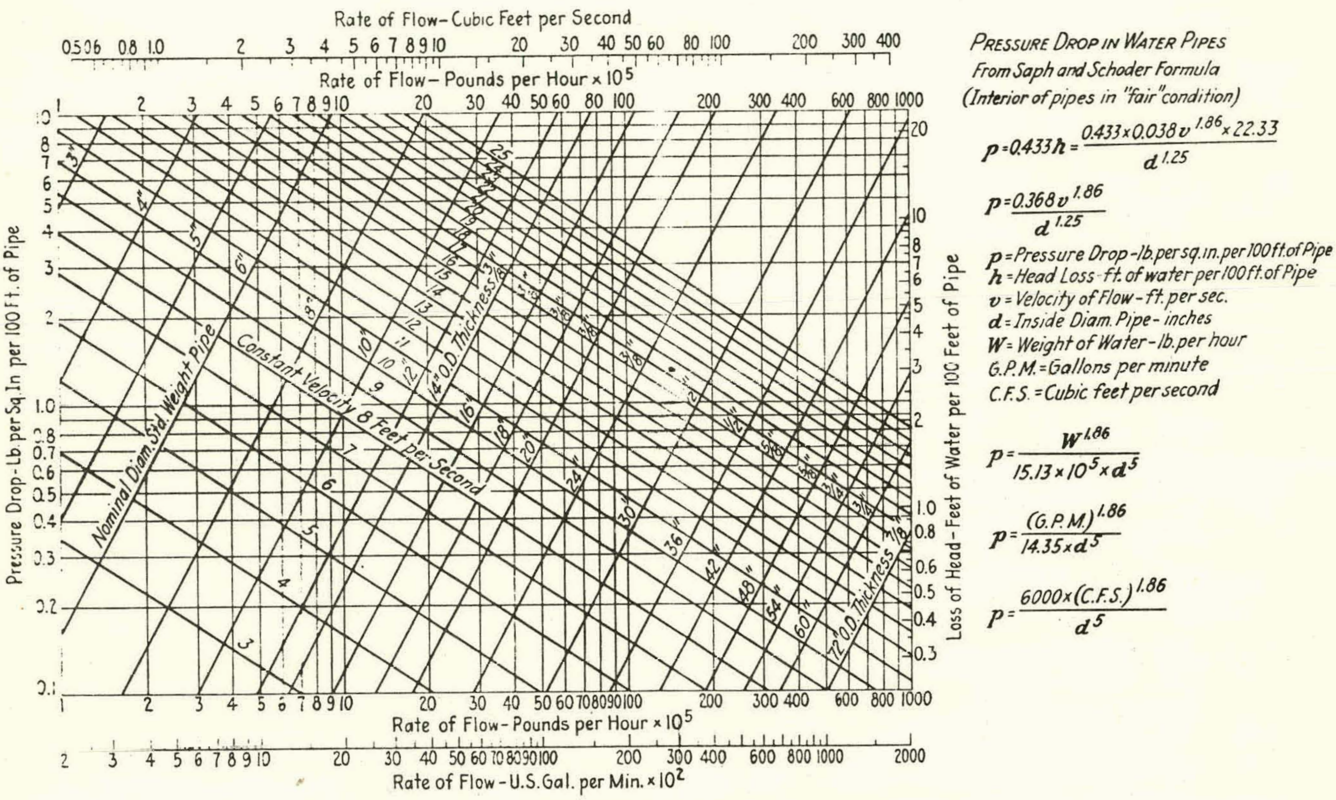


FIGURE II.F-3 PRESSURE DROPS AND PIPE DIAMETERS FOR LARGER FLOW RATES

APPENDIX II.G

BLOWERS AND MOTORS

We studied each storage module to determine the need for blowers and we defined blower specifications such as air or ammonia blower, single or variable speed blower, static pressure. Price quotations were obtained for blowers, motor and drive, OSHA belt guard, and vibration rail base. Prices obtained were in 1978 dollars and were based on forecasted units requirement per year.* Prices are delivered prices, and are F.O.B. factory price plus, on average, 4% more to cover freight within a 600 mile radius area. Prices include blower, variable inlet vane control, if required, motor and drive, vibration rail base and OSHA belt guard, if required. The graph attached can be used to determine budget prices for different capacity (CFM) requirements: i.e., air blowers.

*Discounts on prices run as follows:

5% for quantities 10 to 20 units
10% for quantities 21 to 100 units
15% for quantities above 100 units.

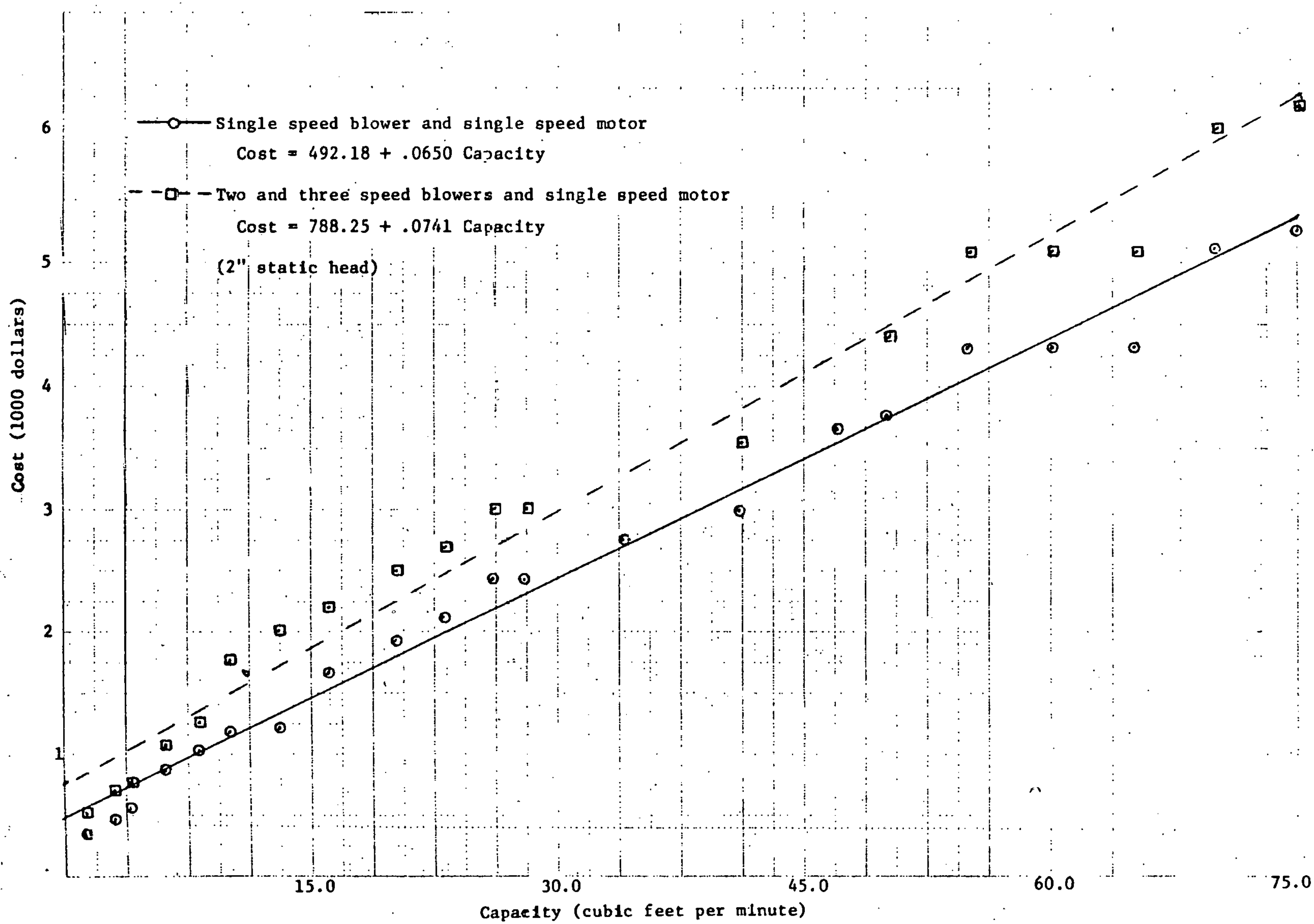


FIGURE II.G-1 COST OF AIR BLOWERS

APPENDIX II.H

PUMPS AND MOTORS

Having determined the fluid pumped, flow rate and head requirement for each pump, we obtained quotes for the pumps, motors, bases and guards. The prices obtained were in 1978 dollars and were based on forecast units per year.* Prices are delivered prices, and are F.O.B. factory price plus, on average, 4% more to cover freight within a 600 mile radius area. Price includes pump, motor, base and guard if required. Figure II.H-1 can be used to determine budget prices for different capacity (GPM) requirements i.e., methanol, ethylene glycol and Dowtherm J.

*Discounts on prices run as follows:

5% for quantities 10 to 20 units
10% for quantities 21 to 100 units
15% for quantities above 100 units.

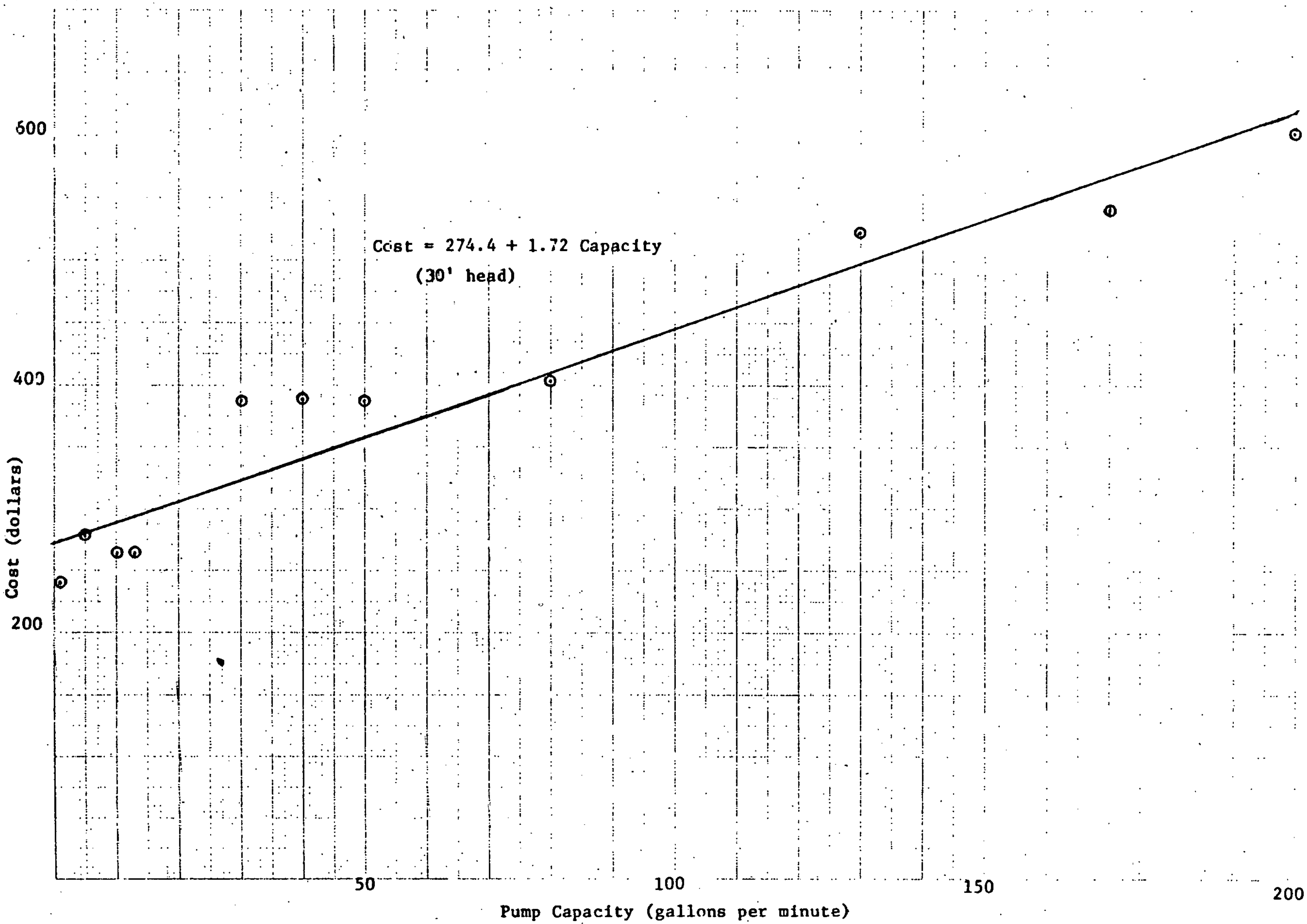


FIGURE II.H-1 PUMPS AND MOTORS FOR METHANOL 100%, ETHYLENE GLYCOL DOWTHERM J

APPENDIX II-I

CONTROLS

I. Controls

Estimating the cost of controls can only be done after all other system elements have been defined and sized. The first step in the costing procedure is to identify the various control elements in the system. These fall into four basic categories which are:

- Sensors
- Power actuated valves and ducts dampers
- Contactors
- Motor starters

Each of these elements is discussed below.

- Sensors:

Table II.I-1 shows the different types of sensors which are normally encountered in thermal storage systems and a cost to be used with each type of sensor. These costs represent an average value for different kinds of sensors, based on cost estimates received from various vendors. Three different kinds of thermal controls are shown. The simplest is a bimetallic switch normally used as a safety switch rather than for normal cycling switching. The thermal switches can be used as thermostat controls. Thermocouple controllers are more expensive and are typically used when a precise level of control is required. For most thermal storage devices this level of control complexity is not necessary.

- Power Actuated Valves and Motorized Ducts:

Table II.I-2 presents cost of various types of motorized valves and ducts. The cost of the one most closely matching the particular application or an interpolated value between two should be used for cost estimating.

- Contactors:

Contactors are used to apply power to most devices requiring more than an ampere to start them. Typically they would be used for larger power actuated valves, heating elements etc. The smallest unit is suitable for starting a 1 1/2 horse power motor or less, which can be started with a direct contact. Larger motors should be started with the devices shown below. Table II.I-3 contains contactor costs.

TABLE II.I-1

SENSORS

	$
Bimetallic Switch	5
Thermal Switch (bellows type)	35
Thermocouple Controllers	81
Pressure Switch	20
Level Switch	10
Fusible Link	1

TABLE II.I-1

POWER ACTUATE VALVES & DUCTS

	Cost ($)
Solenoid	
1/2"	35
1 1/2"	112
Motorized Dampers	
16 lb-in (maximum duct area 12 ft.^{2})	110
40 lb-in (maximum duct area 30 ft.^{2})	115
Ball Valves	
1/2"	129
1 1/4"	170
1 1/2"	183
2"	200
4"	1321
6"	1875
Gate Valves (Steel)	
6"	828
8"	1389
10"	1729

TABLE II.I-3

CONTACTORS

Amperes		
10	NEMA 00	$40
20	NEMA 0	49
30	NEMA 1	56
50	NEMA 2	110
100	NEMA 3	184
150	NEMA 4	415
300	NEMA 5	980

- Motor Starters

Table II.I-4 presents cost for one and two speed motor starters in different size ranges. Three speed starters are approximately twice as expensive as two speed starters.

Some systems may require special noncorrosive materials or other restrictions resulting from the type of material used in the storage system. In these cases, it is necessary to get specific information from a supplier of the device required.

- Controllers

Controllers were estimated at $10 per element plus $60 per item mounted in a cabinet.

TABLE II.I-4

MOTOR STARTERS

Full Voltage Starters	
HP	$
1.5-2	45
3-5	55
7.5-10	62
10-25	116
25-50	190
40-100	421
75-200	985
Two Speed Starters	
2-3	216
5-7 1/2	230
10-20	398
25-40	594
40-75	1520
75-150	2990

Distribution of ANL/SPG-11

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E.J. Croke
A.B. Krisciunas
K.S. Macal
W.E. Massey
R.O. Mueller (180)
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