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A SOLAR DISTRICT-HEATING SYSTEM
USING SEASONAL STORAGE FOR THE
CHARLESTOWN, BOSTON NAVY YARD
REDEVELOPMENT PROJECT

by

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ABSTRACT

This report presents a preliminary analysis for a seasonal storage solar heating system for the Charlestown Navy Yard in Boston, Massachusetts. The area occupies a prominent location in the Boston Harbor and is being redeveloped for residential and commercial use. The system makes use of two large, buried concrete storage tanks totalling 5700 m³ as a water heat store. Other storage facilities, including a dry dock, offer additional solar opportunities for the Navy Yard as the redevelopment progresses.

The analysis makes extensive use of MINSUN, a computer performance and economic simulation routine written specifically for solar seasonal storage systems. The system performance and economics are analyzed for different collector types and areas, component costs, exogenous economic conditions, and optional inclusion of a heat pump.

System cost-effectiveness is defined in relation to an economic break-even situation with respect to a conventional system, and is presented in terms of a solar premium, which is the incremental cost for the solar system per MWH of conventional fuel displaced. Results indicate a solar premium of about \$15/MWH for parabolic collectors and \$10/MWH for advanced CPC evacuated tubes given estimated 1985 collector costs. Cost-effective solutions are found for these two and for flat plate collectors assuming projected collector costs for year 2000. Optimally sized systems for this case exhibit a solar fraction around 0.50 for the 2200 MWH annual heat load; at this point the system is volume constrained. The sensitivity of these results with respect to system parameters and economic assumptions is presented.

The additional analysis and design considerations necessary before an implementation phase are outlined. System implementation is discussed in terms of the roles of the various parties involved and funding/financing possibilities.

1. EXECUTIVE SUMMARY

A. Introduction

Solar energy heating systems using seasonal storage are a most promising alternative to conventional heating means, particularly in northern climates such as New England. These systems exhibit significant economies of scale making them applicable for larger loads and district heating schemes. The International Energy Agency has devoted a particular task to the development of seasonal storage systems and this project has been done in collaboration with the U.S. team at the Argonne National Laboratory.

The Charlestown Navy Yard (CNY) is located in the Boston Inner Harbor and served the U.S. Navy for 175 years until 1974. A large portion of the Yard is now in the process of being redeveloped under the direction of the Boston Redevelopment Authority (BRA) into residential and commercial buildings and public area. The western most section is maintained and operated by the National Park Service (NPS) and is a main tourist area in Boston. Figure 1.1 shows a schematic site plan of the Yard highlighted with the various opportunities for solar systems which are discussed next.

B. Solar Energy Opportunities in the CNY

The attraction of the Charlestown Navy Yard as a site for a seasonal storage system stems from the availability of substantial storage facilities. A number of facilities exist around the Yard so as redevelopment progresses various opportunities can be considered.

Figure 1.1 Charlestown Navy Yard--Schematic Site Plan

This study focuses on the use of two large concrete underground tanks totaling 5700 m³ located in the NPS area. One of the tanks is divided completely in half by a concrete wall; therefore three distinct volumes actually exist. The tanks were built in the 1940s but preliminary inspection indicated that the tanks are in good condition. All are filled to near the top and no leakage is suspected.

Two smaller buried concrete tanks and an underground pump house exist in the redevelopment area and offer opportunities for seasonal ice storage for air conditioning or for a diurnal storage working in conjunction with a larger seasonal storage system.

A most intriguing and unique storage facility available in the Navy Yard is the dry dock located at the far eastern end by the proposed hotel. For aesthetic reasons it is necessary to keep the appearance of the dry dock as an open body of water, and therefore the idea of setting up a salt pond has been considered. Due to the depth of the facility, additional collectors (beyond the salt pond surface area) would be required to take advantage of the large storage capacity available. Various design options have been analyzed and are included as an appendix. The redevelopment of the area around the dry dock will not occur for 7-10 years, so this opportunity was not pursued in detail.

Areas for collectors are available on the flat roofs of the two taller buildings in the Yard. These areas should be sufficient for the system analyzed in this report provided most of the unusual roof structure can be eliminated. Compared to conventionally designed seasonal storage systems, these collector sites are fairly distant and

elevated, thus piping and pumping requirements and heat loss will be greater. A preferable collector site in terms of pumping and piping exists on a two-story office building just to the west of the Navy Yard, though this structure is first to be renovated and plans and structural capability are uncertain.

An extensive underground tunnel network existed in the Navy Yard for the distribution of steam heat. A large portion of the network has been destroyed in the redevelopment area though in the NPS area it is still intact. The distribution network layout for the system analyzed in this study makes use of the walk tunnel along 1st Avenue and the long Ropewalk (Building 58).

For practical and political reasons, the NPS buildings around the large storage tanks are used as the heat load for the system. The buildings were determined to have an annual heat load of about 2000 MWH and a hot water demand of 19,100 Watts. The buildings include apartment units, office space, room for social functions, and a museum.

System Summary

- Storage: Tanks 220 and 221 in NPS area (5700 m³)
- Collector Sites: 1) Buildings 149 and 199 in redevelopment area
2) Two-story office building (to be renovated)
- Distribution Network: Takes advantage of NPS walk tunnel and Building 58
- Load: NPS buildings surrounding storage tanks (2000 MWH space heat, 19,100 Watts hot water)

C. Summary of System Analysis

Methodology. The analysis of this system was performed with extensive use of the computer simulation routine MINSUN written by the Swedish team in the IEA project. The computer model was written specifically for seasonal storage systems and is capable of performance and economic analysis. System cost-effectiveness is indicated by the system solar premium (SOLPRM) which is the incremental cost of the system per MWH of conventional fuel displaced. This variable thus accounts for the system cost as well as its solar fraction and is directly translated to the objective function of cost-effectively displacing conventional fuel.

System Input Parameter File. The important system parameters required as input to MINSUN are listed in Table 1.1. Cost information for collectors was derived from a study done as a part of the U.S. effort in the IEA program [3]. Other costs and product information were gathered through communications with companies in the particular industry. These parameter values were used as a base case and were then systematically varied for a sensitivity analysis.

Base Case Analysis. The performance of the system is shown in Figure 1.2 for the four collector types considered--flat plate (FLPT), evacuated tubes (EVAC), advanced CPC evacuated tubes (ADEVAC), and parabolic trough concentrators (PARB). The most crucial observation to note from this graph is that the system solar fraction (proportion of load met with solar energy) continues to increase significantly as collector area is increased beyond the area sufficient to heat the

Figure 1.2 System Performance--Base Case

storage volume to its maximum allowable temperature. Although the additional energy collected during the summer months is wasted, the additional winter collection is substantial.

Table 1.1

Summary of Base Case Input Parameters

Storage Volume	5700 m ³				
Storage Insulation Thickness	0.076 m (3 inches with R = 7/inch)				
Space Heat Load	2000 MMH				
Tap Water Load	19,100 Watts (167 MMH annually)				
	<u>Year</u>	<u>FLPT</u>	<u>EVAC</u>	<u>ADEVAC</u>	<u>PARB</u>
Collector Costs	1985	270	300	300	350
(\$/m ²)	2000	200	200	200	200
Storage Renovation Cost	\$6/ft ² surface area				
	\$846/m ³ insulation (derived to account for total cost)				
	\$218,915 total				
Distribution Cost (Collector and Load)	\$60/m; \$102,480 total				
Discount Rate (real)	4.0 percent				
Fuel Escalation Rate (real)	3.5 percent				
Aux/Conventional Fuel Cost	\$0.05/kWh				

System cost-effectiveness (SOLPRM) using the 1985 collector cost scenario is shown in Figure 1.3. The collector cost for FLPT, ADEVAC, and PARB are such that all exhibit comparable solar premiums in the range of \$10-\$17 MMH of fuel displaced. Year 2000 cost scenario produces cost-effective (negative SOLPRM) solutions for FLPT, ADEVAC,

Figure 1.3 System Cost-Effectiveness--1985 Collector Costs

and PARB collectors. System solar fraction in the range of minimum SOLPRM is about 0.50 which is very low for typically designed seasonal storage systems. In this case the system is volume-constrained and increasing the load decreases the average annual storage temperature, thereby increasing collector efficiency, and thus more conventional fuel is displaced though the solar fraction is reduced (due to the larger load).

Of particular importance in Figure 1.3 is that the optimal system cost-effectiveness is insensitive over a surprisingly broad range of collector area. This observation implies that the marginal value of the additional solar heat provided by the incremental area is more or less equal to the collector marginal cost. Provided available area for collectors is not a constraint, the selection of a larger area is preferable so that more conventional fuel is displaced.

Sensitivity Analysis. A sensitivity analysis was performed by observing the change in SOLPRM due to iterative changes of parameters of interest, with all other parameters set at the base case. The results of this analysis is presented for ADEVAC collectors (2500 m², 1985 cost) in Table 1.2. Results for the other collectors and collector cost scenarios (in terms of relative change) are similar. SOLPRM is particularly sensitive to the following parameters--load, collector cost, discount rate, and auxiliary/conventional fuel cost.

Heat Pump. It is suspected that including a heat pump in the system will improve system performance and cost-effectiveness. The storage capacity is the primary constraint on the system and optimal

operation is characterized by substantial winter collection and summer heat wasted. A preliminary analysis was done which indicated improved cost-effectiveness with smaller optimal collector area and greater solar fraction. This analysis was performed with insufficient understanding and confidence in the computer model, so these findings should not be considered inerrant or complete.

Table 1.2
Summary of Sensitivity Analysis
(for ADEVAC, 2500 m², 1985 cost)

Parameter		SOLPRM \$/MWH	Parameter		SOLPRM \$/MWH
Load	1000 MWH	28.79	Discount Rate (real)	2 percent	-3.32
	*2000	12.16		*4	12.16
	3000	6.58		6	28.73
	4000	2.48			
Collector Cost	\$200/m ²	-6.30	Fuel Escalation Rate (real)	2.5 percent	18.63
	* 300	12.16		*3.5	12.16
	400	30.62		4.5	4.68
Storage	\$4/ft ²	6.77	Auxiliary Fuel Cost	\$0.04/kWh	25.67
	*6	12.16		*0.05	12.16
	8	17.55		0.06	-1.35
Distri- bution Cost	\$30/m	8.38			
	*60	12.16			
	90	15.95			

*Base case value.

D. Implementation Considerations

Interest in further pursuing this project towards an implementation phase has been indicated by the various parties involved, though

funding and other practical considerations have not been directly addressed. A second phase analysis and design project will be required before implementation. Further work to be done as part of this next phase includes the following:

- Further analysis, including
 - heat pump
 - effect of having three separate storage volumes
 - optimal system control
 - simulation comparisons with other models, such as TRNSYS
- Detailed Cost Estimates
- More careful tank inspection (empty if feasible)
- Further investigation of potential collector areas
- Detailed engineering design
- Analyze financing/funding opportunities

Financing of the implementation phase itself should be, to the extent possible, left to the private sector. This system should certainly be viewed as a demonstration system due to the uncertainty and risk involved with its cost and performance. However, the stream of heating payments by the system user can be used to attract private investors seeking normal rates of return provided guarantees are supplied by the government. Additional funding required would need to come through direct government support and may require a small bond issue. The applicability of federal and state tax credits for solar investments may be very important and needs to be considered.

2. INTRODUCTION

A. Seasonal Storage Concept

Space heating of buildings in northern climates has become a substantial expense and in many areas fuel supplies are short or unpredictable. On a macro level fossil fuels are becoming more valuable to conserve for demands requiring their premium qualities.

Low-temperature space heating for residential and commercial buildings is a very important and appropriate application for solar energy. The abundant solar source and the load are, however, out of phase during the yearly cycle. For conventional diurnal (short-term) storage solar systems, large collector area is required to collect enough heat during the winter months to obtain a system solar fraction of typically only 0.50. The expensive collectors then remain essentially idle during the summer months when abundant solar insolation is available.

Alternatively, annual cycle solar systems rely on large, underground storage volumes and relatively smaller collector area. Heat is collected and stored during the summer months (and winter, when feasible) so that a large heat source is prepared to meet the building load during winter. These systems typically supply nearly 100 percent of the load as they are not subject to short-term meteorological variability. Unlike solar collectors, storage volume exhibits substantial economies of scale and thus annual cycle systems are more appropriate for larger loads--such as a community district heating system, an apartment building, school, shopping center, office building

complex, etc.--than they are for individual residences. There therefore exists the opportunity to make a significant savings in non-renewable fuel consumption. Further, a centralized storage facility makes the implementation of these systems more feasible for existing buildings.

The New England area is particularly well-suited for seasonal storage solar systems. First, fuel prices are substantially higher than the U.S. average, and supplies are often limited. The cold winters and relatively low winter insolation in New England makes winter solar collection quite impractical, in contrast to an area such as Denver which has comparable heating load but substantial collectable winter insolation.

B. Charlestown Navy Yard Project Context

This study has been performed in the context of the International Energy Agency Solar Heating and Cooling Program Task VII--Central Solar Heating Plants With Seasonal Storage. This program has afforded international collaboration on system analysis and design methodologies for seasonal storage systems. Presently operating systems are limited primarily to Sweden where a very serious effort is progressing to combine seasonal storage systems with existing or planned district heating schemes.

A major product of the IEA work has been the computer code MINSUN which was written specifically for performance and economic analysis and optimization of seasonal storage systems and which can be run

quickly on relatively small computers. Parts of the code are still being revised. The use of this program for this project is discussed further in Section 6.

The applicability of a seasonal storage system for the Charlestown Navy Yard was first brought to the author's attention in September 1981. At this time, the existence of large underground storage tanks was learned of, followed by the interest of the Argonne National Laboratory Solar Energy Group in this design study. This report documents work done between March and September 1982 under contract to the Argonne National Laboratory. This work was completed while the Principal Investigator was a student in the Technology and Policy Program at the Massachusetts Institute of Technology working under the direction of faculty and staff at the MIT Energy Laboratory.

3. THE CHARLESTOWN NAVY YARD

The Charlestown Navy Yard (CNY) occupies a prominent area in the Boston Inner Harbor (see Figure 3.1) and is of important historical significance, having served the U.S. Navy for nearly 200 years. The Navy Yard was closed by the Department of Defense in 1974, and the 105-acre area is now the focus of a major redevelopment undertaking by the Boston Redevelopment Authority (BRA). An artist's rendition shown in Figure 3.2 viewed in coordination with the schematic site plan shown in Figure 3.3 illustrates the various divisions of the Navy Yard which differ in terms of ownership and usage. The important aspects of the divisions are summarized below.

National Historic Park. Ownership of this area is by the National Park Service (NPS) and the area is not part of the redevelopment effort. The buildings in the NPS area are all presently in use by the NPS as offices, maintenance facilities, housing for Navy personnel, social functions, a museum, etc. The U.S.S. Constitution is permanently docked here and is a main tourist stop in Boston. The solar system presented in this report mainly concerns this area.

Shipyard Park. This park is presently approaching completion and will provide Charlestown with its first public access to the waterfront in nearly 200 years. Water taxi service between downtown and the Navy Yard is anticipated as redevelopment progresses.

Historic Monument Area. This area will remain in the ownership of the BRA and will be leased to private sector entities. Redevelopment is now beginning in this area and will provide commercial space, along

Figure 3.1 Map of Boston Inner Harbor

Figure 3.2 Charlestown Navy Yard--Artist's Rendition

with parking and light industrial usage in the two taller buildings.

New Development Area. This area has been sold by the BRA to a private development firm. This area will be predominantly apartments, condominiums and townhouses. Redevelopment has already been completed and the residents now occupy one building and work will progress eastward over an eight-year period towards the proposed hotel. A marina in this area has already been opened.

These political divisions are presented because the potential for conflicts of interest and problems of planning and timing are quite important when designing a system requiring the coordination between the areas. The design option selected for this system considered this issue, but nonetheless it was infeasible to position the collector array in the NPS area where the storage facilities are found. The Navy Yard is presented as a whole because a number of interesting seasonal storage opportunities exists, as presented in the next section, and could be implemented as the development progresses to the applicable area.

4. OPPORTUNITIES FOR SOLAR ENERGY IN THE CHARLESTOWN NAVY YARD

The opportunities for various seasonal storage solar energy systems exist for the Charlestown Navy Yard. This report deals primarily with the analysis of the most practical and near-term opportunity, though this section presents an overview of other ideas to consider as the redevelopment progresses. The solar opportunities exist due to the availability of substantial storage facilities. Land area is unavailable for collectors though roof area should be adequate. Historical guidelines stipulated by the federal government when the Navy Yard was released from its control essentially constrains the available collector area to the taller buildings in the Yard.

This section will present relevant information on the CNY regarding the storage facilities, areas for collectors, heat distribution, and building heat loads. The site plan in Figure 4.1 marks the location of these items. Lastly, the system selected for detailed analysis in this study will be presented.

A. Storage Facilities

1. Underground Storage Tanks

Two large buried concrete storage tanks exist in the NPS area as shown in Figure 4.1. Their dimensions are shown in Table 4.1 and a photograph of the tank interior during construction in the 1940s is shown in Figure 4.2. Tank 220 is completely divided in two by a concrete wall and was used by the Navy for petroleum storage. Tank 221 was used for water storage. The tops of the two tanks are

approximately 2-2.5 feet below ground surface. Presently, all the tanks are mostly filled but preliminary inspection of the interiors between the water surface and tank roof was possible. The right half of 220 is filled with water with only slight oil on the surface. The left half is filled up to about 4 feet from the top. About 2-3 inches of a thick, oily substance is on top, though below that it is mostly water. Tank 221 was completely filled with clear water, but enough was pumped out to view the interior above the water surface and through the water. The clearness of the water (which has been in there for unknown years) would indicate a tight tank.

Table 4.1

Data on Storage Tanks 220 and 221

	<u>Tank</u>	
	<u>220</u>	<u>221</u>
Depth (ft)	16.48	16.76
Floor Elevation* (ft)	105.18	101.72
Volume (ft ³)	126,948	88,069
(m ³)	3,594	2,492
Surface Area (ft ²)	21,300	15,370
(m ²)	1,979	1,428

*Tide elevations: Mean Low Water 100.00 ft
Mean High Water 109.60 ft.

Figure 4.2 Photograph of Tank Interior

As indicated in Table 4.1, the tank floor elevations are about 5 feet (for 220) and 2 feet (for 221) above the Mean Low Water tide and 4-1/2 feet (220) and 8 feet (221) below the Mean High Water tide. The question of ground water causing significant tank heat loss remains, though a critical problem is not expected. No workers at the NPS (previously employed by the Navy Yard) recalled any ground water problem during any construction, and recently the BRA installed utility piping without any associated problem. Another question to consider is that of tank buoyancy when the tank is emptied for renovation. This is unlikely to cause a problem due to the heaviness of the concrete tanks and again NPS employees recalled working on the tank interiors without the need for surrounding sump pumps.

Two additional sub-surface tanks are also available in the Navy Yard in the Historic Monument Area behind Building 199 as shown in Figure 4.1. These two tanks were used for water storage and have volumes of 712 m³ (Tank 222) and 1400 m³ (223). Both are made of concrete and 222 is cylindrical in shape. The use of these two tanks has not been pursued in detail, though their size makes them attractive as either a diurnal tank for a two-tank seasonal storage system [5] or for seasonal ice storage for air conditioning [6]. Another storage facility for ice exists in the large underground pump house near Dry Dock 2 (see Figure 4.1) which previously housed the large pumps used with the dry dock.

2. Dry Docks

Dry Docks 2 and 5, as indicated on Figure 4.1, offer a most unusual

thermal storage opportunity. Their aesthetic value of being open water must be preserved, but storage would be possible by setting up a solar assisted salt pond or thermally isolating all but the top 1-2 meters of the volume. The dimensions, construction and condition of the two dry docks are presented in Table 4.2.

Table 4.2
Data on Dry Docks 2 and 5

	<u>Dry Dock</u>	
	<u>No. 2</u>	<u>No. 5</u>
Length (ft)	715	512
Width at top (ft)	114.0	98.5
Width at floor (ft)	72.0	86.3
Depth (ft)	38	25
Volume, approx (ft ³)	2.53x10 ⁶	1.18x10 ⁶
(m ³)	71,500	33,500

Dry Dock 2: Constructed of granite rock, sides progress downward in step-like manner. Door to Harbor not present.

Dry Dock 5: Constructed of steel sheets, vertical sides (except near bottom). Door is supposedly still attached though submerged (not visible).

Initial enthusiasm regarding the use of the very large Dry Dock 2 has been dissipated by practical considerations. Primarily, the BRA was not favorable towards using this dry dock which prominently borders Shipyard Park which has been the major focus of their multi-million

dollar work thus far. Additional practical problems concern the size of the undertaking and the lack of time available before redevelopment of the buildings in this area is completed.

Dry Dock 5 offers a more feasible opportunity and one which the BRA and the private developer of this area view with interest. A photograph of the empty dry dock is shown in Figure 4.3. Preliminary design concepts and cost information have been developed for the dry dock storage facility but this system was not pursued as the focus of this study due to its uniqueness and further time horizon before implementation would be considered. The preliminary study concerning this storage facility is included as Appendix A of this report.

B. Collector Area Sites

Adequate sites for collector area in the Navy Yard are limited; ground space is not available, the buildings face southeast, and historical preservation codes will not permit any collectors on low buildings or pitched roofs. Two tall, structurally sound buildings with flat roofs do exist, however, and collectors would most likely not present an aesthetic problem. The two buildings are 149 and 199 (see Figures 4.1 and 3.2). The total horizontal surface areas are tabulated in Table 4.3. It should be noted, however, that particularly on Building 149 unusual roof structure is present. Planning for solar collectors will have to be coordinated with BRA and the private developers so that unnecessary roof structure conflicting with the collector array is eliminated.

Figure 4.3 Photograph of Empty Dry Dock 5

One other area for collectors should be pursued. This is a two-story warehouse with large flat roof area located just outside the Navy Yard across from the berth of the U.S.S Constitution. The structure is owned by the Massachusetts Port Authority and is being redeveloped into office space with 65,000 ft² on each floor.

Table 4.3

Data on Collector Area Sites

	<u>Building</u>		
	<u>149</u>	<u>199</u>	<u>MASSPORT</u>
Floors (above ground)	9/11	8	2
Total Horizontal (ft ²)	83,203	68,292	65,000
Surface Area* (m ²)	7,730	6,344	6,038

*Calculated simply as length x width, i.e., does not account for unusual roof structure present particularly on Building 149.

A large steel elevated road/bridge structure which borders the back of the Navy Yard (evident in Figure 3.2) was also considered as a place for solar collectors. Practical problems of securing the array in a cost-saving and aesthetically permissible manner were not considered surmountable, and this alternative was not pursued.

If interest in using Dry Dock 5 materializes, the design of the new hotel could be such as to accommodate a collector array, along with Building 199, to heat the storage facility.

C. Distribution Network

An extensive tunnel and piping network existed for the Navy Yard for distribution of steam heat. This network has been destroyed (pipes sold for scrap and tunnels collapsed) by the BRA in the western half of their area. New utility lines were laid about one year ago and most of the streets are now finished. In contrast, tunnels do still exist in the NPS area. The tunnels of particular interest are shown in Figure 4.1. The walk tunnel along First Avenue is in decent condition and still has old insulated steam pipes in it (of unknown condition). The concrete-covered tunnel from Tank 220 to the walk tunnel is accessible by re-digging (mainly grass surface). The condition of the conduit from 221 to the walk tunnel is less known.

Additional tunnels exist connecting the remaining buildings of the NPS area so increasing the load connected to the storage tanks could be done at a relatively small expense.

D. Building Loads

The buildings which were of initial interest as heating loads for the system analyzed in this report included the NPS buildings near the storage tanks and the group of BRA buildings in the western half of the Historic Monument Area. These buildings are noted in Figure 4.1 and their dimensions, construction and usage are presented in Table 4.4. The NPS buildings are presently in use and require no renovation. Each building has its own operating heating system using natural gas and consisting of hot water circulating through radiators. Redevelopment of

the BRA buildings is to start very soon and they should be occupied within a year or two. Data obtained on heating loads for the NPS buildings are presented next; those for the BRA buildings could not be calculated with reasonable certainty and the load analysis by the redevelopment firm has yet to be done.

Table 4.4
Data on Building Loads

<u>BRA Area:</u>	<u>Building</u>					
	<u>33</u>	<u>34</u>	<u>36</u>	<u>38</u>	<u>39</u>	<u>Total</u>
Floor Area (ft ²)	40,500	32,814	31,872	79,926	59,325	250,000
(m ²)	3,764	3,050	2,962	7,428	5,513	23,000
Construction	---heavy masonry blocks, 3-1/2" insulation planned---					
Usage	-----offices, small commercial-----					
<u>NPS Area:</u>	<u>Building</u>					
	<u>Museum</u>	<u>Marine</u>	<u>Comman-</u>	<u>C.O.</u>		
	<u>22</u>	<u>Barracks</u>	<u>dant's</u>	<u>Quar-</u>	<u>5 and 4</u>	<u>Total</u>
		<u>I</u>	<u>House</u>	<u>ters</u>		
			<u>G</u>	<u>B-F</u>		
Floor Area (ft ²)	19,402	26,046	8,007	23,680	36,442	113,577
(m ²)	1,803	2,421	744	2,201	3,387	10,555
Construction	-----brick, stone-----					
Usage	Museum/ Offices	Apts./ Offices	Functions/ Tours	Apts.	Apts./ Club/ Dining	

1. Space Heating Load

Reasonable estimates of the space heating loads for the NPS buildings were obtained from past records of fuel consumption. Table

4.5 shows these heat loads averaged over fiscal years 1978, 1979, and 1980. The buildings suffer greatly from lack of basic conservation measures which are presently being implemented. Expectations are for the space heat load for these buildings to be reduced to about 2000 MWH annually.

Table 4.5

NPS Building Space Heat Load

<u>Building</u>	Natural Gas Consumption*	Load**
	<u>(1000 ft³)</u>	<u>(MWH)</u>
I and G	5,105	1145
265 (B-F)	2,356	529
4	5,706	1280
5	269	60
22	1,385	311
Total	14,821	3325

*(Averaged from FY '78, '79, '80.

**Assumed burner efficiency of 0.75.

2. Tap Water Heating Load

The volume of hot water demand and usage for each building is summarized in Table 4.6. On a basis of 50°C ΔT heating requirement (from 10°C in the water service main to a required 60°C) this load is equivalent to a constant demand of 19,100 Watts.

Table 4.6

NPS Building Hot Water Demand

<u>Building</u>	<u>Hot Water Usage</u>
I	5 apartments, occupied year-round (4 persons/apt.)
G	used sparingly, functions once every two weeks
265 (B-F)	5 apartments, occupied year round (4 persons/apt.)
4 and 5	50 people year round, communal bath and dining service (3 meals/day)
22	minimal hot water

Hot Water Demand

10 apts at 4 persons each	40 people x 20 gal/day/person = 800 gal/day
50 rooms of communal bath and dining	50 people x 25 gal/day/person = 1250 gal/day
Museum (22)	10 people x 3 gal/day/person = 30 gal/day
Commandant's House (G)	20 people x 0.3 gal/day/person = 6 gal/day

Total Hot Water Demand = 2086 gal/day = 761,390 gal/yr = 2882 m³/yr

Total Heating Demand = 19,100 Watts (with $\Delta T = 50^{\circ}\text{C}$)

E. System Selection

The opportunity for various seasonal storage solar systems including heat and ice storage makes the Navy Yard of great interest. This study, however, focuses on the use of the two large storage tanks in the NPS area as these are the most conventional for seasonal storage and most feasible for near-term implementation.

Originally, the NPS expressed no concern about using their tanks for heating the BRA buildings; however, as the work progressed it became evident that the NPS would want to take advantage of their storage facilities for their own heating load. Furthermore, the NPS area is presently in functioning order and collaborating with them would avoid the time-constrained coordination between the numerous groups beginning work on the redevelopment area. The NPS area also has substantial portions of the distribution system in place. The area is visited by many tourists throughout the year so public awareness of the system would be created. A detailed design and implementation phase may find broader opportunities for monetary support as the NPS is a federal agency.

Although no area for solar collectors exists in the NPS area, the BRA feels the use of Building 149 would be allowed by the historical code and the developers. The building is believed to be structurally sound though the presence of various structures on the roof may cause a problem. Compared to a conventional seasonal storage system design, the collector array would be fairly distant from the storage, and pumping requirements relatively large due to the distance and height of the building. The two-story building across from the U.S.S. Constitution would be a better site though the plans for this building and its support capability are uncertain at this time. In either case a cost for use of the roof space should probably be expected.

5. SYSTEM COMPONENT DESIGN AND COST

An extensive effort was made for this project to gather realistic cost information for the implementation of this system. This task primarily involved becoming familiar with technical and product alternatives and soliciting performance and cost data from the industry. Cost and performance information for solar collectors were obtained from work currently in progress for the IEA Task. This section will present the information collected for each major system component--storage, collectors, and distribution--and other products considered, specifically water pumps and heat pumps. No specific reference to companies is made here, though a list of the companies contacted is included in the References.

A. Storage

1. Design

Little choice is available for this system but to insulate the storage tank on the interior surface. The insulation will need to be effective at temperatures up to 100°C and able to withstand about 20 feet of water pressure (approximately 10 psi). Ease of installation in terms of necessary support structure and access into the tanks is also important along with a water-resistant property. The insulation will be isolated from the water storage by a liner which must also withstand the 100°C maximum temperature. The liner installation may prove difficult due to the ceiling and vertical walls, and tank support columns and input/output piping. The seaming characteristics of the

liner product is thus also important. Optimum design and placement of the collector and load loop heat exchange piping in the storage units also needs to be considered in greater detail than was done in this preliminary study.

2. Cost

a. Cleaning and Inspection

The two storage tanks will first have to be emptied, cleaned, and inspected for deterioration. The cost involved for this task is quite uncertain and dependent on problems encountered, but should not constitute a major part of the total renovation job. None of the tanks are suspected of leaking. Tank 221 is filled with clear water, though Tank 220 may require proper disposal of the oily product in the left half and a major cleaning.

b. Insulation

A summary of the various insulation products, characteristics and costs obtained from the industry is presented below.

Loose Fill Perlite Insulation

Loose fill insulation made from popped volcanic rock, Silicon-coated so moisture-proof. R3.12/inch, \$1/ft³
Installation would require aluminum framing to hold perlite. Flat sheets of aluminum cost about \$1.50/ft² plus supporting braces and large access into the tank would be needed. Does not seem as economical or practical as other alternatives.

Foam Glass

R2.86/inch, excellent water-resistant property, 100 psi compressive strength. Comes in boards. Cost: \$0.50/board foot (1 ft x 1 ft x 1 inch). Some sources thought foam glass to be expensive and difficult to install.

Urethane Foam Spray

Suggests spray application as boards would require clips and wide

access into tank. Spray foam has R7/inch. Good compressive strength. Needs clean, dry surface to apply. Cost: approx. \$5/ft² for 3" thickness (includes installation labor).

A Recommended Renovation Using Urethane Foam

The following renovation procedure and cost was recommended by one company.

1) spray concrete with primer	\$0.10-0.15/ft ²
2) spray 1.5-2" urethane foam (may need more)	\$2.25-2.50/ft ²
3) spray elastomeric waterproof coating, 10-20 mils thick	
4) liner TPU (Thermo-plastic-urethane)	\$1.25/ft ² installed
TOTAL: Approx. \$4.00-4.50/ft ²	

Quoted Estimate With Urethane Foam

A rough estimate for 3" urethane foam spray for the total tank surface area was \$70,000, or approximately \$2.00/ft² including installation/labor. This may be optimistic.

c. Liners

Liners will be needed in the storage tanks to provide a barrier between the water and insulation. Liners need to be long-lasting and able to withstand steady temperatures around the 100°C range. A number of materials have been recommended and price quotes received.

DuPont XR-5

DuPont XR-5 (not EPDM) Style 8130
Derivative of PVC but heat-resistant up to 220°F, can be heat-sealed. Price \$0.57/ft²

Industrial-Grade Hypalon

Has been used on solar ponds with good performance but temperature never exceed 170-180°F. Price \$0.60/ft².

EPDM

EPDM, reinforced with nylon, withstand constant 180°F

Thickness	0.045"	0.060"
Price, \$/ft ²	0.89	1.00 (includes fabrication, seaming)

The ability of the liners to withstand 100°C has not been sufficiently demonstrated for long periods of time and thus claims by industry must be carefully checked.

Installation cost for the liner is very uncertain and project dependent and could not be ascertained informally and accurately over the phone. An approximation suggested, though, is a cost equal to the liner itself.

d. Storage Renovation Cost Summary

From the above cost and performance data an idea of the total cost of insulating the tank interior can be obtained. The total surface area requiring insulation in the two tanks is 36,670 ft² (3407 m²). Assuming a desired insulation value of R20, this would require 7 inches of foam glass at \$3.50/ft² (not installed) or 3 inches of urethane foam spray at \$5.00/ft² (installed). Liner prices will likely be on the order of \$1.00/ft² (installed). A total price range is indicated below.

	36,670 ft ²
\$4/ft ²	\$146,680
\$6/ft ²	220,020
\$8/ft ²	293,360

B. Collectors

The collector array clearly comprises the greatest portion of the total system cost. This is particularly true at present-day costs which are, however, expected to drop significantly as production levels

increase. The choice of collector type entails a trade-off between cost and performance which forms a major part of the system analysis presented in Section 6.

Data for collector cost and performance were obtained through the U.S. effort for the IEA Program [3]. The state of collector technology and industry, of course, makes this sort of cost and performance summary a formidable task, but this data source is most up-to-date and comprehensive.

Collectors considered for this system were flat plate (FLPT), evacuated tubes (EVAC), advanced compound parabolic concentrator evacuated tubes (ADEVAC), and parabolic trough concentrators (PARB). FLPT and EVAC collectors are relatively well commercialized and mature in their development. ADEVAC collectors were developed at Argonne National Laboratory and are presently entering a commercial phase. An important characteristic of these collectors is their ability to concentrate without the need for tracking the sun. PARB collectors are commercially available though further development and cost-reduction is expected. PARB collectors require a tracking system.

1. Collector Performance

Collector performance is presented in the manner required by the MINSUN computer routine. Performance is described by the following equation:

$$E = F_R (1 - \tau_\alpha) K_{\tau\alpha} - F_R U_L (T_i - T_{amb}) / I - (F_R U_L)^2 (T_i - T_{amb})^2 / I^2$$

where $K_{\tau\alpha}$ is an incident angle modifying factor for insolation angles

other than normal. The values used to represent collectors used in this study are as follows:

<u>Collector Type</u>	<u>F_R</u>	<u>$F_R U_L$</u>	<u>$(F_R U_L)^2$</u>	<u>K_{Ta}</u>
FLPT	0.808	4.33	0.0	0.10
EVAC	0.51	1.30	0.0	0.17
ADEVAC	0.70	1.00	0.0	0.17
PARB	0.807	0.089	0.869	0.0

2. Collector Cost

Collector costs used in this design analysis were derived from the information collected for this purpose for the IEA Program [3]. Two cost scenarios are considered--one near-term (1985) which is the approximate time horizon for system implementation, and one projected for year 2000 when collector costs are reduced to expected values for a mature production facility. Costs are quoted in $\$/m^2$ and are derived to include installation, plumbing, pumps and controls, site preparation, and distribution and profit. The following table summarizes the cost data used:

<u>Collector Type</u>	<u>Cost ($\\$/m^2$)</u>	
	<u>1985</u>	<u>2000</u>
FLPT	270	200
EVAC	300	200
ADEVAC	300	200
PARB	350	200

C. Distribution System

A number of distribution layout alternatives for the collector and load loops was considered. The most attractive alternative is shown in Figure 5.1 and Table 5.1 summarizes the pipe and excavation requirements for the network and the average total lengths. The layout takes advantage of existing tunnels in the NPS area and the long Navy Ropewalk (Building 58), thereby minimizing expensive insulated pipe-in-pipe and excavation requirements.

Cost for the distribution network is derived as shown below from indicated specific costs obtained from the industry.

Insulated Pipe	3500 ft at \$10/ft = \$35,000
Pipe-in-Pipe	2700 ft at \$15/ft = 40,500
Excavation	925 ft at \$12/ft = 11,100
TOTAL	\$86,600

D. Other Costs

1. Water Pump

Two pumps will be required in the system--one for the collector loop and one for the load distribution network. Cost for a pump able to deliver 2 gallons/second over a 500-foot head was quoted at \$8,100. Specifications were 100 hp, 3450 rpm wheel pump operating at 460 volts, 3 phase, and 124 amps. A \$10,000 order-of-magnitude price is applicable to both the collector and load loop. This amount would represent \$3-4/m² for the collector array (which is already included in the collector cost). The cost is about 10 percent of the

Figure 5.1 Distribution Network--Alternative Selected

Table 5.1
Pipe and Excavation Requirements for Distribution Network
(Collector and Load Loop)

<u>Pipe Section (from Fig. 5.1)</u>	<u>Length (ft)</u>	<u>Pipe Type</u>	<u>Section Description</u>
1	150	insulated pipe	up and down 149
2	190	buried pipe-in-pipe	149 to 58
3	1000	insulated pipe	along 58
4	100	buried pipe-in-pipe	58 to Marine Barracks
5	125	buried pipe-in-pipe	Marine Barracks to 221
6	300	buried pipe-in-pipe	221 to 220
7	210	buried pipe-in-pipe	221 to 1st Avenue
8	600	insulated pipe	along 1st Avenue

Totals:

Insulated pipe: $(150 + 1000 + 600) \times 2 = 3,500 \text{ ft}; 1067 \text{ m}$

Buried pipe-in-pipe:

Pipe length: $(190 + 100 + 125 + 125 + 300 + 300 + 210) \times 2 =$
2,700 ft; 823 m

Excavation length: $(190 + 100 + 125 + 300 + 210) = 925 \text{ ft}; 282 \text{ m}$

Average collector loop length:

$[(150 + 190 + 1000 + 100 + 125) + .6(300)] \times 2 = 3490 \text{ ft}; 1064 \text{ m}$

Average load loop length:

$[\cdot 4(300) + (125 + 210 + 600)] \times 2 = 2,110 \text{ ft}; 643 \text{ m}$

distribution network cost and will be included for the load loop. Operating costs for the pumps have not been considered in this stage and are not modeled with MINSUN.

2. Heat Pump

The analysis of this system considers the effect of including a heat pump in the system. The approximate sizing of the heat pump compatible with the system is derived in Section 6. The capital cost for the heat pump was quoted at \$20,000-\$25,000, though the operating expense will be seen to be the more significant cost.

6. ANALYSIS OF CNY SYSTEM PERFORMANCE AND COST-EFFECTIVENESS

A. Methodology

This study has made extensive and exclusive use of the computer routine MINSUN (Version II)* written by the Swedish group and revised by the Canadians as part of the IEA program. MINSUN is written specifically for seasonal storage systems, uses daily time intervals, and produces system performance and economic data and is capable of optimization. A more detailed description of the program is available elsewhere [14,16] but the basic outline of the program system flow is shown in Figure 6.1. UMSORT combines collector performance data and meteorological data to create an input file for MINSUN which tabulates the amount of energy collected per m^2 for a range of collector input temperatures. ADVANCE allows the user to begin the yearly simulation on a specified day other than January 1st. This analysis was performed using Boston TMY (Typical Meteorological Year) data with simulation beginning on April 1st, the approximate end of the heating season and time of minimum storage temperature.

The analysis called for in this and similar design studies requires multiple runs of MINSUN, often with iterative changes in particular variables. This procedure proved tedious and time-consuming, requiring editing of each MINSUN input file and searching through each output file for desired variables. A routine which proved most useful was written to edit automatically the input file, run MINSUN, and supply and output file with only the output variables specified (one line for

*Information regarding MINSUN is available from Argonne National Laboratory, Solar Energy Group, Bldg. 362, Argonne, Illinois 60439.

MINSUN SET OF PROGRAMS - OVERVIEW

Figure 6.1 MINSUN Program Flow

each MINSUN run). The routine, called MINREP, is documented in Appendix B and is available for use.

System cost-effectiveness is determined by a new variable added to MINSUN which accounts for annual system cost as well as the system performance. Preliminary analysis showed that different systems could result in similar annual costs (or cost per MWH of load); but this information alone failed to capture the performance of the system in terms of displacing conventional fuel which is the basic objective. In other words, these cost data alone would not indicate the clear preference of a system with equal cost per MWH but greater solar fraction as another system.

The more critical datum required is essentially the premium one must pay per MWH of conventional fuel displaced by the solar system. (Premium is positive if solar system is not cost-effective on straight economic terms.) The variable SOLPRM is calculated as follows:

$$\text{SOLPRM} = \frac{\text{CSTMWH} * \text{LOAD} - \text{CSTCNV} * \text{LOAD}}{f * \text{LOAD}} = \frac{\text{CSTMWH} - \text{CSTCNV}}{f}$$

where CSTMWH = annual system cost divided by total load

(COSTOT/THLOAD in MINSUN)

CSTCNV = conventional fuel cost per kWh * 1000 * AFUEL

(AFUEL as in MINSUN)

f = system solar fraction.

This variable assists the decision maker by reducing the decision to how much extra (if premium is positive) is worthwhile to pay to displace conventional fuel. This would be similar to adding a premium to the conventional fuel cost to account for price uncertainty, risk of

supply disruption, other externalities, and the positive benefits of implementing solar.

B. System Input Parameter File

The basic parameter input file for MINSUN used to describe the CNY system is reproduced in Figure 6.2. The required parameters are fairly self-explanatory and their meanings are documented elsewhere [14]. The CNY system has some features incompatible with the input file requirements, and the manner in which these parameters were dealt with and the reasoning behind the selection of other important parameters is described next. The remaining values were either presented in Section 5 or were set at values considered reasonable and which were used by the sample input file included in the MINSUN documentation.

Storage. MINSUN models the sub-surface storage facility as a cylindrical tank specified by the input parameters volume and height. The storage available in the Navy Yard is actually two rectangular tanks (one of which is divided in half). The two most critical parameters for performance are the storage volume and surface area, so storage height was derived to model the actual total tank surface area using the following relationships,

$$\text{Volume} = \pi r^2 h$$

$$\text{Surface Area} = 2\pi r^2 + 2\pi r h$$

where r = tank radius and h = tank height.

For the CNY system, storage volume was determined to be 5700 m^3 (reduced from gross tank dimensions to account for volumes of

CHARLESTOWN NAVAL YARD OPTIMIZATION OPTION
SING CENTR NOHEATPUMP

```

*
*
INSULATION
* COLL NETW      EARTH      DIAM      FIX
* INSULATION     TEMP      DEPENDENT  INSULATION
*   COND
*   W/M/K        C          M          M
*
*   .03         10.        0.         .05
*
*
COLLECTORS
* OPTION          AREA  TEMP  DTMAX  TMAX1  DUMMY  TMAX2  NORMAL  MAX
* 3 FOR IEA      STEP
* OPTION
*              M2    C
*              C    KG/S/M2 KG/S/M2
*
*   3           2500. -0.0  10.    50.   -0.0  97.    .003  .01
*
*
* NETWORK  INSUL  PIPE
* LENGTH  THICK  DIAM
*          NESS
*   M      M      M
*
*   532.   -0.0   .056
*
*
STORAGE
*
* VOLUME  HEIGHT  NUMBER  DENSITY  GROUND  START TEMP IN EACH SEGMENT
*          OF
*          SEGMENT
*   M3      M      KG/M3    C          C
*
*   5700.   3.97   3        1000.   20.    60.0  45.5  41.0
*
*
* INSULATION THICKNESS  THERMAL COND  OPTION  THICKNESS
* LID WALL  BOTTOM  LID  BOTTOM  10R20R3  OF
*          WALL  W/M/K  TEMP DISTR  CONCRETE
*          M
*
*   .076 .076 .076 .02 .02 .02    3    .51
*
*
HOUSELOAD AND DISTRIBUTION
* NUMBER OF WITH  K-  INDOOR  OPTION  OPTION  FEED TEMP HOUSE
* HOUSE  AREA  VALUE  TEMP  WAY  RETURN  EKV. PARAMETERS
*        M2  W/M2/K  C
*
*   1.    2000. 12.896  20.    3      1    55. 1.5 0. 45.
*
*
* HUMAN  TAPWATER  HOUSELOAD  INSULATION  PIPE
* POWER  POWER    NETWORK    THICKNESS  DIAM
*        LENGTH
* W/HOUSE W/HOUSE  M          M          M
*   0.    19100.  322.    .05    0.10
*
COST
*

```

Figure 6.2 Charlestown Navy Yard System: Base Parameter Input File for MINSUN (p.1 of 2)

```

* COLLEC ASYMPT SPECIFIC SIZE BETA DEPTH GROUND CONCRETE INSULATION
* TOR STORAGE FOR SMALL OF SML COST
* STORAGE STORAGE EXP
* $/M2 $/M3 $/M3 M3 /M $/M2 $/M3 $/M3
*
* 300 0. 0. 5000. 0.0 0.0 0.0 0. 846.
*
* CONDEN EVAPO HEAT PUMP AREA LENGTH PIPE AUX HOUSE FUEL
* SER RATOR EL MOTOR DISTRI DISTRI INSULA HEATING
* INSTALLED BUTION BUTION TION INSTALLED
* $/K/W $/K/W $/W $/M2 $/M $/M3 $/W $/KWH
*
* 0.0 0.0 0. 0. 60.0 0. 0. 0.05
* ELCOST DEPRECIATION INTEREST REAL INCREASE
* TIME ENERGY PRICE
* $/KWH YEAR PER CENT PER CENT
* 0.00 20. 4.0 3.5
*
*
* OPTIMIZATION
* OPTION MAX CONVERGENCE
* PRINT NR OF PARAM
* EVERY POINT FOR MIN
* XXXPOINT CALC DIRECTIONS POINT
*
* 1 600 2.E-6 2.E-6
*
* OPTION VARIABLE VARIED
* COLL STORAGE INSUL HEAT PUMP TAP HEAT PUMP HEAT
* AREA VOL DEPTH THICKN EVAPOR COND EVAPOR COND
* 1 0 0 0 0 0 0 0
*
* BASIC STEP LENGTHS FOR EACH VARIABLE
*
* 100. 1000. 10. .2 10. 10. 10. 10.
*
* PARTS OF STEPLENGTHS FOR THE FIRST TRIALS
*
* .01 6. 10.
*
* DISTANCE FROM BOUNDARY WHERE PENALTY STARTS
*
* 10. 50. 100. 100. .01 .0001 .01
* .05 1 .1 .1 .5 .01 9999.
*
* PENALTY AT BOUNDARY
*
* 1. .04 .01 .01 1.E6 1.E10 1.E6
* 1.E4 1.E4 1.E4 1.E4 1.E6 1.E6 0.
*
*
* COLLECTOR STORAGE STORAGE SOLAR
* AREA VOLUME DEPTH COVER
* MAX MIN MAX MIN MAX FACTOR
* M2 M2 M3 M3 M
*
* 20000. 0. 50000. 0. 50. 0.0
*
*
* END

```

Figure 6.2 Charlestown Navy Yard System: Base Parameter Input File for MINSUN (p.2 of 2)

insulation and support columns) and total surface area is 3407 m^2 .

The above system of equations yields two solutions; one for a tall skinny tank and one for a more realistic shape which is described as follows:

Volume = 5700 m^3	Height = 3.97 m
Surface Area = 3407 m^2	Radius = 21.38 m

Storage insulation was modeled as 3 inches of urethane foam at R7/inch.

Space Heat Load. The MINSUN routine essentially models a district heating system with a specified number of houses with identical heating requirements. This modeling decision does not accommodate the CNY case of a number of very different buildings or the case where heat loads (in MWH) are known but the buildings' heat loss areas and k-values are not known. Experimentation with these MINSUN parameters showed that non-realistic, dummy values could be used without loss of computational accuracy to model a desired MWH heat load. The k-value chosen for the CNY system was derived to produce (with Boston TMY data) an annual heating requirement of 1 MWH/m^2 of building area. The area parameter is nominally set at 2000 to produce the estimated 2000 MWH load but can be easily altered for analytic purposes.

Capital Costs. Capital costs for the CNY system were divided into only three parameters which were selected to account for the total cost of each component--collector, storage, and distribution. Collector costs were set at values presented in Section 5. Collector type and area are not pre-specified but remain as the primary dependent variables in the system analysis. Storage renovation/insulation cost

was lumped in the insulation cost parameter (in $\$/\text{m}^3$) and was derived as follows:

Total Renovation Cost = \$200,000 (from Section 5)

Insulation Volume = Surface Area x Insulation Thickness

$$= 3407 \text{ m}^2 \times .076 \text{ m} = 260 \text{ m}^3$$

Storage Cost/ m^3 Insulation: $\$846/\text{m}^3$

Distribution cost for the collector and load loops was lumped in the parameter calling for cost in $\$/\text{m}$ of distribution length. Total length is 1707 m, total cost was set at \$102,420 to account for pump capital and operating costs (see Section 5), thereby resulting in a parameter value of $\$60/\text{m}$.

Auxiliary Fuel Costs. The NPS recently installed new heating units in the buildings of interest so zero capital costs were specified for auxiliary heating. Presently, the NPS pays about $\$0.03/\text{kWh}$ for their natural gas heating. The value used as a base in this analysis is $\$0.05/\text{kWh}$ figuring that with recent decontrol this is a likely price for a two-year time horizon when this system may be implemented. For the heat pump analysis a cost for electricity of $\$0.10/\text{kWh}$ is used. NPS is presently paying this amount and this value was not increased to a 1985 projection to offset the fact that the fuel escalation rate was chosen with natural gas in mind.

Economic Parameters. System depreciation time is 20 years. Discount rate is nominally set at 4 percent (real). Fuel escalation rate is 3.5 percent (real), which causes a real doubling in the fuel costs just by the end of the 20-year system lifetime.

C. Base Case Analysis

The important system parameters are summarized below in Table 6.1. The base case is analyzed with varying collector type and area; only these two parameters remain and are of vital interest. The analysis is divided into a look at system performance (independent of all cost/economic assumptions made) and system cost-effectiveness.

Table 6.1

Summary of Base Case Input Parameters

Storage Volume	5700 m ³				
Storage Insulation Thickness	0.076 m (3 inches with R = 7/inch)				
Space Heat Load	2000 MWH				
Tap Water Load	19,100 Watts (167 MWH annually)				
	<u>Year</u>	<u>FLPT</u>	<u>EVAC</u>	<u>ADEVAC</u>	<u>PARB</u>
Collector Costs	1985	270	300	300	350
(\$/m ²)	2000	200	200	200	200
Storage Renovation Cost	\$6/ft ² surface area				
	\$846/m ³ insulation (derived to account for total cost)				
	\$218,915 total				
Distribution Cost (Collector and Load)	\$60/m; \$102,480 total				
Discount Rate (real)	4.0 percent				
Fuel Escalation Rate (real)	3.5 percent				
Aux/Conventional Fuel Cost	\$0.05/kWh				

1. System Performance

Figure 6.3 summarizes the system performance for the four collector

types and varying area. The solar fraction is low relative to typical seasonal storage systems due to the fixed storage volume and relatively large load, though the amount of conventional fuel displaced is in accordance with systems having this same storage size. In terms of performance, EVAC collectors are least effective, followed by FLPT, and ADEVAC and PARB. The switch in rank between ADEVAC and PARB performance is explained by the fact that ADEVAC collectors make better use of diffuse sunlight and thus a smaller area is sufficient to raise the storage temperature up to 95°C during the spring/summer. At larger areas, storage temperature for both ADEVAC and PARB systems reach this maximum and PARB collectors perform better at these high temperatures when diffuse insolation is not efficiently collected.

An important result seen in Figure 6.3 is that the system solar fraction continues to rise significantly as area is added beyond the area sufficient for the storage temperature to reach its maximum allowable temperature. A slight decrease in the f vs. area slope is noticeable when the system becomes volume-constrained but the additional area still contributes significantly to the load by collection during the winter. The additional collection during the summer is wasted as storage temperature already reaches its maximum in time for the heating season. This observation is further evident in Figure 6.4 which plots the day on which the average tank temperature reaches 90°C (Day 1 = April 1) versus area. At large areas, ADEVAC collectors meet this requirement in June, PARB in early July, and FLPT in early August. Thus a large part of the collection season is not

Figure 6.3 System Performance--f and T_{max} --Base Case

Figure 6.4 Day of Seasonal Cycle When Storage Becomes Constrained--Base Case

used efficiently as the system is constrained by the storage. Whether or not this constrained operation is nonetheless worthwhile (due to increased winter collection) depends on the economics.

A convenient manner to more directly examine the system performance simulation is to plot the storage temperature and important heat flows over the annual cycle. This information is presented in Figures 6.5 and 6.6 for 2000 and 2500 m² of ADEVAC and FLPT collectors respectively. The heat flow curves are for cumulative values over the year.

ADEVAC collectors heat the storage volume to its maximum temperature in a much shorter time period than FLPTs. Even at 2000 m², the limited volume constrains the ADEVAC collector operation for a substantial part of the summer and fall. 2500 m² of FLPT collectors seems to provide the typical sinusoidal temperature curve for a seasonal storage system. Independent of collector type and area, the stored heat (approximately 350 MWH) is used to provide heating for about 50 days, from the middle of October to early December. For the remainder of the heating season, auxiliary fuel is used primarily though the collectors also supply a portion of the heat required.

2. System Cost-Effectiveness

The system cost-effectiveness is analyzed in terms of its solar premium (SOLPRM) which is the additional cost of the system per unit of fuel displaced (\$/MWH) over the conventional alternative. This variable thus accounts for both the system cost and its solar fraction. Figures 6.7 and 6.8 present these data for 1985 and 2000

Figure 6.5 Annual Performance Simulation--ADEVAC Collectors

Figure 6.6 Annual Performance Simulation--FLPT Collectors

Figure 6.7 System Cost-Effectiveness--1985 Collector Costs

Figure 6.8 System Cost-Effectiveness--2000 Collector Costs

collector cost assumptions. The shapes of the curves show that the marginal value of adding collector area is at first very great and then reaches a broad region of collector area where the marginal value remains very small (positive and then slightly negative). Continuing these curves to larger collector areas, one would expect the SOLPRM to continue rising at an increasing rate as the solar fraction levels off and the system eventually becomes load constrained. Beyond the areas plotted the system can be characterized more and more as a diurnal system. Space available for collectors in the Navy Yard will also be a constraint. It is evident, though, that the system reaches an optimal cost-effectiveness between 2000 and 3000 m² and is surprisingly independent of collector area in this range. SOLPRM is more sensitive to collector area when collector cost is greater.

Figure 6.7 shows that at near-term (1985) collector costs, the solar system would require an additional expenditure of \$10-\$17/MWH of fuel displaced. Current costs are such that FLPT, ADEVAC, and PARB collectors all result in rather similar cost-effectiveness. EVAC collectors are clearly inferior. Year 2000 projected costs are used to derive Figure 6.8. FLPT, ADEVAC, and PARB collectors all become cost-effective with ADEVAC and PARB resulting in a \$5-\$10/MWH savings.

Throughout the remainder of the analysis, EVAC collectors have been dropped as they afford inferior performance at the same cost or more than ADEVAC and FLPT. In order to concentrate on the sensitivity of other parameters, collector area has been set at 2500 m². Thus, the results vary only slightly from the true minimum SOLPRM. At this area

all collector types at both cost scenarios are very close to the optimal cost-effectiveness.

3. Single System Analysis

(ADEVAC, 2500 m² at \$300/m², Base Case Parameters)

A simulation was run of the base case system with 2500 m² of ADEVAC collectors at the 1985 cost (\$300/m²). The system cost is summarized as follows in Table 6.2. The heat flow performance for this system is presented in Table 6.3.

D. Sensitivity Analysis

The following analysis is divided between those parameters affecting the performance of the system, those directly affecting its capital cost, and those which define the exogenous economic conditions. SOLPRM will be dependent on all these parameters, though the heat flow performance will only be dependent on the first group.

Table 6.2

Single System Analysis--Cost Summary

Total Capital Cost	\$1,071,395
Collectors	\$750,000 (70.0 percent)
Storage	218,915 (20.4 percent)
Distribution	102,480 (9.6 percent)
Operational Cost	\$ 60,197
Total Yearly Cost (annualized)	\$ 163,520
Cost per MWH	\$75.45/MWH
Cost Conventional per MWH	\$69.86/MWH
SOLPRM	\$12.16/MWH (of displaced fuel, f = 45.98)

Table 6.3

Single System Analysis--Heat Flow Summary

<u>Collector Sub-System</u>			
Collector Output	1420.87 MWH		
Pipe Loss Forward	17.13 MWH		
Pipe Loss Return	20.38 MWH		
Collector Supply		1383.36 MWH	
<u>Storage Sub-System</u>			
Storage Losses	378.89 MWH		
Collector Supply Minus Storage Losses		1004.47 MWH	
Stored Heat Year End Minus Year Beginning	-20.23 MWH		
Collector and Storage Supply		1024.70 MWH	
<u>Auxiliary</u>			
Auxiliary Pump Electric Energy	0.00 MWH		
Auxiliary Heater	1203.94 MWH		
Total Supply		2228.64 MWH	
<u>Load</u>			
Dist. Loss Forward	34.73 MWH		
Dist. Loss Return	26.59 MWH		
House Load	2167.33 MWH		
Total Load		2228.64 MWH	
<u>Ratios</u>			
Collector Supply/Total Load	62.07 percent		
Collector Supply Minus Storage Losses/Total Load	45.07 percent		
Collector and Storage Supply/Total Load	45.98 percent		

1. Performance Parameters

Storage Insulation Thickness. An important cost/performance trade-off exists for storage insulation. Its effect has been analyzed for a 2500 m², 1985 cost, ADEVAC system and the results are plotted in Figure 6.9. Cost for insulation alone was determined to be \$564 m³ (or \$4/ft²) for the base case of 3 inch thick, spray urethane with R7/inch. From the solar fraction curve one observes a substantial

Figure 6.9 Sensitivity Analysis--Storage Insulation Thickness

improvement as insulation is added up to around 0.08 m. An economic optimum is reached around this point as seen by the SOLPRM curve. The base value of 0.076 m (3 inches) is thus determined to be a reasonable value. One would expect very similar results for other collector types and areas.

Load. The space heating load in the Navy Yard is not firmly fixed. The buildings closely surrounding the storage tanks are expected to have an annual load of 2000 MWH though other buildings could be connected at relatively little cost due to the present existence of piping tunnels. From Figure 6.10 one sees that system cost-effectiveness responds favorably to increasing load. Although the solar fraction is reduced to normally unheard of levels for seasonal storage, the same system displaces a greater amount of fuel due to the lower average storage temperature and greater collector efficiency. As seen in Figure 6.11, this performance benefit remains quite significant for loads up to 4000 MWH.

Figure 6.12 plots the system cost-effectiveness versus ADEVAC collector area (1985 cost) for varying space heating loads. One observes a substantial decrease in SOLPRM between 2000 and 3000 MWH and a nearly cost-effective solution for a 5000 MWH load. As load increases, the optimal collector area increases but remains in the 1500 to 2500 m² range. Large loads may cause a large daily temperature change in the storage volume which raises uncertainty regarding the modeling accuracy by MINSUN which can be checked by comparison with a simulation using hourly time steps. The importance of the load

Figure 6.10 Sensitivity Analysis--Space Heat Load

Figure 6.11 Effect of Space Heat Load on Solar System Supply

Figure 6.12 SOLPRM vs 1985 ADEVAC Collector Area Varying Load

parameter, however, remains clear.

Figure 6.13 shows a similar result for the tap water load. This load (on an annual basis) is on the order of one magnitude less than the space heating load so the effect on SOLPRM is much less significant in the range of practical values.

2. Cost Parameters

Capital cost of the solar system is divided into three components--collector, storage, and distribution. As will be seen, SOLPRM responds linearly to changes in capital cost; the derivative depends on the relative size of the change.

Collector Cost. Until collector costs are substantially lowered as expected, collectors will remain the predominant capital expenditure, especially in this system where storage is relatively inexpensive. The critical role of this cost was seen in Figures 6.7 and 6.8 where the two cost scenarios resulted in opposite cost-effectiveness implications, positive SOLPRM for 1985 costs and negative SOLPRM for year 2000. Figure 6.14 varies collector cost through a wider range and plots the effect on SOLPRM for each collector type. Economic break-even collector costs per m^2 , given base case assumptions, are shown in Table 6.4.

Table 6.4

Economic Break-Even Collector Costs

	<u>Break-even Cost (\$/m²)</u>
FLPT	200
EVAC	165
ADEVAC	235
PARB	258

Figure 6.13 Sensitivity Analysis--Tap Water Load

Figure 6.14 Sensitivity Analysis--Collector Cost

Storage Cost. Figure 6.15 shows the sensitivity of SOLPRM to storage insulation/renovation cost. Being a substantially smaller fraction of the total cost than the collectors, the change in SOLPRM is much less sensitive for a reasonable range of storage costs.

Distribution Cost. As seen in Figure 6.16, SOLPRM is also rather insensitive to distribution cost, which comprises a small fraction of the total capital expenditure.

3. Economic Parameters

Discount Rate. The sensitivity of the system cost-effectiveness to the discount rate is shown in Figure 6.17. Clearly, this parameter has a marked effect on SOLPRM and can render a cost-effective solution or not for both cost scenarios for the plotted range of real discount rates (2-6 percent). This system will service the federally-owned National Park Service and thus an argument can be made for the use of a lower social discount rate which would more equitably distribute wealth and resources between present and future generations. A higher discount rate might be considered more appropriate for capital investments of private firms with good investment and growth opportunities.

Fuel Escalation Rate. Figure 6.18 shows that SOLPRM is also quite sensitive to the fuel escalation rate. This fact makes an implementation decision difficult since this variable is so uncertain. The National Park Service uses natural gas which is presently fairly inexpensive but should escalate at a greater rate (than oil) given recent decontrol.

Figure 6.15 Sensitivity Analysis--Storage Insulation/Renovation Cost

Figure 6.16 Sensitivity Analysis--Distribution Cost

Figure 6.17 Sensitivity Analysis--Discount Rate

Figure 6.18 Sensitivity Analysis--Fuel Escalation Rate

Auxiliary Fuel Cost. Presently the NPS pays about \$0.03/kWh for natural gas. The base case assumption for this analysis is \$0.05/kWh as this is a likely price for a two-year time horizon when the system may be implemented. The base fuel escalation rate of 3.5 percent would cause a real doubling of this price just by the end of the 20-year system lifetime. Figure 6.19 shows that system cost-effectiveness is strongly dependent on the auxiliary/conventional fuel cost selected. For example, selecting a fuel price of \$0.06/kWh, perhaps to account for reasonable externalities, renders cost-effective solutions for the 1985 collector cost scenario.

Although the price of natural gas will escalate more quickly than oil, it will probably never exceed oil on absolute dollar terms; therefore a system displacing natural gas will be less competitive than the same system displacing oil.

E. Preliminary Heat Pump Analysis

This solar system operates optimally in a volume-constrained manner with substantial summer collection wasted. This observation implies that a heat pump would be an appropriate means essentially to increase the heat storage capacity. With a heat pump one could design for the storage temperature to reach a minimum of 10°C at the end of the heating season. At this reduced temperature, collector efficiency is enhanced and collection can continue unconstrained for a longer time over the greater ΔT . The solar energy collected and stored over this greater ΔT is then available to meet the load. Average annual storage

Figure 6.19 Sensitivity Analysis--Auxiliary Fuel Cost

temperature is significantly less so storage losses are reduced.

Economic trade-offs include the following factors--heat pump capital cost, heat pump operational cost, reduction in optimal collector area, and greater solar fraction.

An approximation of the size heat pump required was calculated as follows:

Operational Period: December 15 through March 30 (105 days) (from non-heat pump simulation it was observed that storage dropped to the minimum temperature required for heating about December 15).

Heat Pump ΔT Range: $\Delta T = 45^{\circ}\text{C} - 10^{\circ}\text{C} = 35^{\circ}\text{C}$

Heat to be Pumped from Storage = Heat stored in 35°C ΔT + Heat Added by Collectors = 230 MWH + 270 MWH
= 500 MWH

Heat Flow Rate (Refrigeration of Storage) = 500 MWH/105 days =
200 kW = 56 tons.

Conversations with a heat pump manufacturer indicated a heat pump of this size would cost between \$20,000 and \$25,000. Power input to the compressor would be 82 kW and a typical C.O.P. would be 3.4.

Over the operational period, the compressor would require about 82 kW x 105 days x 24 hrs/day or 200 MWH electrical input. The National Park Service is presently paying \$0.10/kWh for electricity so the first-year operational cost would be about \$20,000, and is thus a much greater expense than the annualized capital expenditure.

A preliminary effort was made to analyze the effect of including a heat pump in the system. This analysis indicated improved cost-effectiveness with smaller optimal collector area and greater solar fraction. However, insufficient confidence and documentation for

using the heat pump routine in MINSUN makes this analysis uncertain and incomplete. A new heat pump routine was recently added to MINSUN and will be used for further analysis.

7. SYSTEM IMPLEMENTATION

The idea that this system might actually be implemented has acted as an important catalyst in furthering the interest of the various parties directly involved. What the implementation would entail and how a decision would be made has not been formally considered, however; nor has any willingness to commit funds been indicated. This section first describes the perspectives of the parties which have a role to play, then outlines further work required before an implementation phase, and concludes with an overview of funding/financing possibilities.

A. Perspective and Role of Parties Involved

Argonne National Laboratory. As the U.S. representative to the IEA Program, the Solar Energy Group at Argonne is expected to pursue a specific design study and implementation as stipulated by the IEA for each contributing country. The CNY system is presently a major candidate for this role. Being a Department of Energy laboratory, ANL is potentially a critical link to federal funds. The present federal solar budget, however, is very lean and may not permit a substantial commitment. ANL does have the computer design tools and experts in the field to assist or lead in any future work and as a member of the IEA would provide international attention to this system.

Boston Redevelopment Authority. The BRA has an important role to play on a local level. Their direct interest in this system has been diminished since the decision to heat the NPS buildings was made,

but their involvement now is important. The solar system would no doubt be connected by the public with the redevelopment project as a whole. The solar collectors will be placed in the BRA territory so work will have to be done in close coordination with them and the private development firm they choose to work in this area. The other seasonal storage opportunities involving the dry dock and other underground tanks for diurnal heat or ice storage would very directly require the involvement of the BRA. The budget for the BRA is controlled by the city and is also tight, but the strong backing of this Authority for the solar project may be helpful in obtaining city or state support for a final design analysis and implementation project.

National Park Service. Being the users of the heat supplied by the solar system, the NPS is, of course, directly involved. Employees at the Yard have indicated that innovative means of conserving energy is strongly supported by the NPS which is presently on a zero growth energy demand mandate, and thus those employees have been particularly interested and helpful in supplying needed drawings and information. The use of the NPS maintenance crew, which works full-time at the Yard, as a labor force for some of the construction tasks may be a worthwhile possibility. As a federal agency in the Department of the Interior, another important access to federal funds can be pursued.

Massachusetts Executive Office of Energy Resources. The MEOER has not been directly involved in this study except for occasional informal briefings of progress made. An interest by this office in seasonal storage systems does exist and its applicability and potential for this

State is understood. State funds in Massachusetts are presently in a particularly bad situation, but this office would be in the best position to lobby for support.

B. Implementation Procedure

This section briefly considers the work required to implement the CNY system once such a decision is reached. This design study concludes a first, preliminary phase which should be adequate to base a decision on whether or not to proceed.

A final stage preceding implementation will be required to provide a more detailed analysis and simulation of this system along with a detailed engineering design including a detailed cost appraisal. The MINSUN simulation should be checked against other models such as TRNSYS, and collector manufacturers should be involved to obtain specific cost estimates and performance specifications. The other potential collector site (the two-story buildings across from the U.S.S. Constitution) should be pursued and data obtained on the structural capabilities of the roofs. If feasible, the tank interiors should be inspected more carefully; Tank 221 should be able to be readily emptied and Tank 220 should be emptied at this stage if the oily product can be inexpensively disposed of. Analysis should be made to determine the effect of having three separate storage volumes and the effect of associated storage control options. The engineering design should provide detailed specifications and drawings needed to proceed with a construction phase.

C. Funding/Financing Possibilities

Whether or not the CNY system is determined to be cost-effective by the MINSUN routine, the system should clearly not be expected to attract private sector investors on its own merit. Once the technology has been proven and diffused, private sector financing opportunities become available, but uncertainty and risk involved in this application make these methods ineffective on their own. To this extent it is reasonable to view the CNY system as a demonstration system providing the designers and the marketplace with otherwise unobtainable worthwhile cost and performance data. The promise of seasonal storage solar systems to displace large quantities of conventional premium fuels and their success in Sweden are clear reasons to encourage the diffusion of these systems. The appeal of the CNY system as a demonstration is great in terms of the information it would afford and its visibility and the attention it would attract.

The fact that, at worst, the system is not tremendously far from being cost-effective implies that direct subsidy might be held to a reasonable level with proper financing and risk taking by the government.

The NPS at the Navy Yard could be expected to pay for the heat supplied by the solar system at a rate near the displaced conventional cost. This steady stream of payments can be used to attract investors willing to put up an amount of capital which would afford them a reasonable rate of return. The risk involved could be limited by guarantees by the government in case the system fails to perform up to

expectations. Alternatively, the NPS or Department of the Interior or Department of Energy could supply this capital and the government retain the stream of energy costs. The remainder of the required capital might be obtained by direct subsidy by the federal and/or state government out of present funds or through a small bond issue.

The applicability of the federal and state tax incentives for solar investments to the various financing/ownership schemes needs to be carefully considered and may improve system cost-effectiveness substantially. The possibility that private investors would be allowed tax credits would essentially increase the proportion of the total capital that could be raised in the private sector.

Third Party Financing. Third party financing offers an attractive means to raise capital for projects with relatively long paybacks. The private sector investors may be solicited from the surrounding community so that the local energy balance of payments do not deteriorate the local economy. In essence, the investors form a firm selling heat at a rate competitive with alternative means.

Particularly for a demonstration system, investors demanding a reasonably low rate of return will insist on purchase guarantees by the system user and/or a rate of return guarantee by the government.

The cash flows describing the financing scenario greatly depend on the present tax laws and the tax status of the investor group. These laws are subject to change but this analysis is based on the present laws analyzed in greater detail in Reference [4]. As a firm, the investors would be entitled to a general investment tax credit (ITC) of

10 percent, an energy tax credit (ETC) of 15 percent, and accelerated depreciation allowances using a five year schedule with the following yearly percentages--15 percent, 22 percent, 21 percent, 21 percent, and 21 percent. These tax credits are effective provided the firm has an adequate tax liability from which to deduct the credits. No tax rebates are allowed. This requirement seems particularly prohibitive for the envisioned small group of investors whose only taxable income will be the received heating payments. A number of means may be available to nonetheless capture these tax advantages. The ITC and ETC can be carried forward as far as 15 years (though the present value of the credit is reduced). Leasing arrangements can be made through another company with adequate tax liability to recover the tax provisions. The solar investors can be a broader based firm with an already sufficient tax burden. Subtleties in the tax law need to be carefully considered in detail once a more specific financing and government assistance arrangement is made. These involve the at-risk limitations for the tax credits and leasing provisions, "double-dipping" limitations for government subsidized financing, qualifications for the ETC of equipment not solely used for the solar system (i.e., the distribution system carrying heat derived from conventional fuel), and the applicability of advantageous small-business tax legislation.

Example. The following example provides a net present value analysis of an investment scenario for the CNY system consisting of 2000 m² of ADEVAC collectors using 1985 costs and all base case

parameters. The scenario assumes adequate tax liability, a 46 percent corporate tax rate, 8 percent inflation (12 percent nominal discount rate), a State solar investment tax credit of 9.5 percent (presently available in Massachusetts), and disregards the specific subtleties mentioned above along with considerations regarding debt versus equity financing. The system capital cost is \$929,315 and the system displaces 905.78 MWH of fuel annually.

Net Present Value of Cost

i) Investment = \$929,315

ii) ITC = (.10)(929,315) = \$92,932

iii) ETC = (.15)(929,315) = \$139,397

iv) State Credit = (.095)(929,315) = \$88,285

v) Depreciation Year	1	2	3	4	5
Amt Depr	139,397	204,449	195,156	195,156	195,156
PV	139,397	182,544	155,577	138,908	124,025
ΣPV	\$740,451				

PV(Tax Shield) = (.46)(740,451) = \$340,607

Therefore,

$$\begin{aligned} \text{NPV of Cost} &= \$929,315 - 92,932 - 139,397 - 88,285 - 340,607 \\ &= \$268,094 \end{aligned}$$

Net Present Value of Energy Payments

$$\begin{aligned} PV &= (905.78 \text{ MWH})(\$50/\text{MWH}) \sum_{j=1}^T \left(\frac{1 + \text{FLA}}{1 + d} \right)^j = (905.78)(50)(19.05) \\ &= \$862,755 \end{aligned}$$

Taxes = (.46)(862,755) = \$396,867

Therefore,

$$\text{NPV of Energy Payments} = \$862,755 - 396,867 = \$465,888$$

NPV of Investment

$$\text{NPV} = \$465,888 - 268,094 = +\$197,794$$

This simplified example does show the importance of the tax provisions in reducing the value of the capital expenditure. Provided an adequate tax liability is available, the use of third party financing appears attractive as a capital formation strategy.

The diffusion of these larger solar systems depends strongly on private investment and financing. Therefore, it is attractive to demonstrate the various opportunities available and involve, to the extent feasible, this facet of system implementation in the CNY system.

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The following companies were contacted for product performance and cost information:

Insulation

Daley Foam Products, Inc., Cambridge, Massachusetts
 Dow Chemical Company, Midland, Michigan
 Dyer Insulating Contractors, Newark, New Jersey
 Perlite Institute, Inc., New York, New York
 Pittsburgh Corning, Pittsburgh, Pennsylvania
 Owens Corning Corporation, Toledo, Ohio
 Spray-On Systems, Inc., Boston, Massachusetts
 Upjohn Chemicals, New Haven, Connecticut

Liners

Carlisle Tire and Rubber Company, Carlisle, Pennsylvania
 Protective Coatings, Inc., Fort Wayne, Indiana
 Shelter Rite Division, Seaman Corp., Millersburg, Ohio
 Watersaver Company, Inc., Denver, Colorado

Piping

Johns-Manville, Denver, Colorado

Water Pump

Ingersoll-Rand, New York, New York

Heat Pump

Borg-Warner Thermoelectrics, Chicago, Illinois
Carrier Airconditioning Group, Syracuse, New York

Partition Materials (for Dry Dock)

Glar-Wall Corporation, Fort Wayne, Indiana
Resolite Company, Zelienople, Pennsylvania
Reynolds Metals Company, Construction Products Division, Richmond,
Virginia

Salt (for Dry Dock)

Cargill, Inc., Salt Division, Watkins Glen, New York
International Salt Company, Clark's Summit, Pennsylvania
Morton Salt Division, Chicago, Illinois

Sand (for Dry Dock)

A.A. Will Sand and Gravel Company, Canton, Massachusetts
Boston Sand and Gravel Company, Boston, Massachusetts
West Sand and Gravel Company, Boston, Massachusetts

APPENDIX A

PRELIMINARY DESIGN AND COST ANALYSIS FOR DRY DOCK 5 STORAGE FACILITY

I. Design Options for Dry Dock 5

Three redesign options for the dry dock as a thermal storage facility are considered in terms of cost and performance. Each design calls for a salt pond at the surface in order to 1) maintain the aesthetic appearance of the dry dock as an open body of water, 2) as a means to both collect energy and store it below, and 3) to avoid constructing an insulated cover for the dry dock. The volume of the dry dock is such that the salt pond alone would be insufficient to make use of the available heat storage capacity so additional collectors will be required to add heat to the bottom section. The large buildings on either side of the dry dock (hotel and apartments/condominiums) are to be developed in a later phase of the work which has already begun on the western region of the area. At present, the expectation is that the area around the dry dock will be completed during a period 7-10 years hence. The private redevelopment firm expressed initial interest in the salt pond concept and saw no obvious barriers to prevent such a system. The general understanding was that there was no reason to pursue a detailed engineering or implementation phase until the plans for that area are much further along.

The three design options for the dry dock are a) deep salt pond, b) sand storage/salt pond and c) fresh water storage/salt pond. These ideas are illustrated in Figure A.1 and are discussed below, first in terms of their design and performance and then in terms of costs

specific to each alternative. All three designs will likely require insulation of the bottom and sides of the dry dock and a liner around the dry dock surface area.

A) Deep Salt Pond. This design calls for a typical salt gradient through the first five feet of the volume with a saturated salt solution (S.G. = 1.23) filling the bottom 15+ feet. The salt pond would create a typical temperature profile at the top of the storage and heat from solar collectors would be added at the bottom and would rise to merge over time with the upper salt pond, but remain trapped in the heavy brine. The main advantage of this design is its relative simplicity. Disadvantages are that 1) there is no thermal isolation between the two portions of the facility so heat loss due to gradient mixing would be larger and 2) a heat exchanger would be necessary for the collector and load loop to avoid piping of the corrosive brine through the collectors and pipes.

B) Sand Storage/Salt Pond. The bottom 15 feet of the dry dock could be filled with sand with heat pipes running through it which would support the shallow salt pond above. Insulation could be placed between two liners to thermally isolate the two areas. Otherwise a single liner would be necessary to seal the salt pond. Thermal isolation would allow the salt pond to run much cooler particularly in the late summer/fall and thus the salt gradient would be easier to maintain and heat loss reduced. Periodically, as the salt pond temperature increases, this heat could be pumped below. The major performance disadvantage of this design is the reduction of storage

capacity due to the lower heat capacitance of sand (approximately 25 BTU/ft³/°F, dry, versus water at 52 BTU/ft³/°F) and thus less load able to be met. Adjustment for this difference will need to be made in the overall economic analysis.

C) Fresh Water Storage/Salt Pond. This design would also allow for thermal isolation between the salt pond and main storage. Cost savings from much less required salt or sand must be compared with the cost of a partition to separate the two fluids (with the heavier one on top). Design ideas for the partition are shown in Figure A.2. The partition could be built with fiberglass or galvanized steel sheets separated by I beams for bending strength and filled with sturdy insulation which, along with the sheeting and I beams, would be able to withstand the compressive force. The partition could be supported by the incompressibility of the water below, or by its net buoyancy force as illustrated in Figure A.3. Both sides of the partition would require a liner to prevent fluid flow into the partition.

Depending on the cost and effectiveness of the shallow salt pond for the design options B and C, it can be determined whether to pursue this option or to have the top 5 feet of the dry dock as fresh water not serving any storage/collection purpose. The support requirements of the insulated partition would be reduced and the potential for a large swimming/wading pool (heated by heat loss below) might be considered.

II. Product and Cost Data

A) Salt. Quotes for salt available in the Boston area were as follows:

Industrial solar salt (99.6% NaCl):

\$38/ton + \$5/ton (min) trucking = \$43/ton

Salt treated with Prussian Blue:

\$25.60/ton + \$6/ton trucking = \$31.60/ton

Rock salt:

\$43.70/ton delivered; \$46.65/ton pneumatic delivery

Quantity of salt required for the top 6 foot salt pond with average salt concentration of 15 percent is 1610 tons. Additional salt needed for the deep salt pond alternative (16 feet of saturated salt solution, S.G. = 1.23) would be 7060 tons. Total cost for salt would then lie in the following rate.

	<u>\$35/ton</u>	<u>\$40/ton</u>	<u>\$45/ton</u>
1610 tons	\$56,350	64,400	72,450
7060 tons	247,100	282,400	317,700

Clearly the salt required for the deep salt pond is a large expense.

B) Sand. Sand also is not inexpensive. Quotes obtained are as follows.

1. \$12.50/ton delivered, washed concrete sand
2. \$7.30/ton delivered, washed concrete sand
\$8.80/ton delivered, washed sand/stone 3/4-1.5" stone
3. \$6.95/ton delivered, washed concrete sand
\$9.00/ton delivered, 3/8" stone

\$8.75/ton delivered, 3/4" stone

\$8.50/ton delivered, 2" stone

For a 16-foot depth of sand at 100 lbs/ft³, 40,000 tons are required. Total cost range for sand is thus

	<u>\$7/ton</u>	<u>\$8/ton</u>	<u>\$9/ton</u>
40,000 tons	\$280,000	320,000	360,000

C. Partition. The design and construction of this partition to separate the fresh and salt water certainly involves a much more serious engineering challenge. Cost data will be much more uncertain and at present are not complete. The partition cost has to be compared with the cost of the displaced salt or sand also accounting for the performance benefits of thermal insulation and large heat storage capacitance. Limited price quotes for materials have been obtained for various products normally used for building siding.

Fiberglass reinforced plastic panels:

$$\$1.50/\text{ft}^2\text{--for } (50,000 \text{ ft}^2 \times 2)(\$1.50/\text{ft}^2) = \$150,000$$

Urethane foam filled galvanized metal wall sections:

$$\$4.35/\text{ft}^2, \text{ delivered--for } (50,000 \text{ ft}^2)(\$4.35/\text{ft}^2) = \$217,500$$

Aluminum flat sheeting, 032 gauge

$$\$1.50/\text{ft}^2\text{--also } \$150,000$$

Additional price quotes are needed for these sorts of material and also for I beam supports, rubber pressure barrier, and design and construction. Compared with the deep salt pond alternative, additional cost for the partition design should include the partition insulation and additional liner needed, but should also account for performance

benefits, salt savings, and less costly piping/heat exchanger requirements.

D. Insulation and Liner

Cost information for insulation and liners is presented in the main text of this report for the storage tank renovation and is also applicable for this present analysis. Surface area (not including the partition) requiring insulation and a liner consists of the bottom and four sides of the dry dock and is about 74,000 ft² (6875 m²). A price range for this task is indicated below:

	<u>\$4/ft²</u>	<u>\$6/ft²</u>	<u>\$8/ft²</u>
74,000 ft ²	\$296,000	444,000	592,000

Figure A.1 Dry Dock Renovation Alternatives

Figure A.2 Partition Design

Figure A.3 Pressure Equilibrium Alternatives for Partition Design

APPENDIX B

MINREP DOCUMENTATION

MINREP was written to facilitate the repetitive running of MINSUN to analyze the behavior of output variables with respect to input parameters and system options. In brief, MINREP updates the solar system input parameter file, runs an abridged version of MINSUN, and creates an output file of only the variables specified. The program organization is described below.

```

=====
input files  unit                                output files  unit
MINREP.DAT   3          *****
MINREP.VAR   7          MINREP                   MINREP.OUT   9
SYSREP.DAT   5          *****
                        calls
                        VARMAT
                        MINSUB2                   MINSUB2.OUT   6
=====

```

Input Files:

SYSREP.DAT This file is a formatted version of the MINSUN solar system parameter input file. It is formatted to facilitate changing of specific variables. Each line consisting of input parameters is formatted as 10A7 with each variable right-justified in consecutive seven space slots. MINREP requires direct access of these records which may first requiring running the file thru SYSREP.FOR.

MINREP.DAT This file specifies the changes desired in the input parameter file SYSREP.DAT. Each record consists of the line and position number of the variable to be changed in SYSREP.DAT and the new value. Format is 2I3,A7. The line number and variable position need not be specified for successive records referring to the same variable. If no simulation run is desired (to allow for changing of more than one variable) at least one of the following five spaces must be non-blank.

Line number = 500 specifies a change in collector type; the new collector data file name 'xxxxxxx'.DAT is then specified in the A7 slot.

Line number = 800 is specified if a new set of output variables is desired. Program flow is sent back to reading MINREP.VAR and calling Subroutine VARMAT.

Line number = 700 is specified to run a series of runs with one variable being iterated. The following line of MINREP.DAT gives the line number, variable position, starting value, ending value, and iteration step size in the following format; 2I3,3I7.

Line number = 999 should be specified as the last card in the file causing the program to STOP.

MINREP VAR This file specifies the variables to be included in the output file (maximum of 20). The first record consists of the number of variables desired (I3); the following records contain the MINSUN Fortran variable names !!!right-justified!!!, one per line, in an A7 format. Any of the system input or output variables which normally comprise the main MINSUN output file (LUW) can be specified. Collector type can also be included in the output file by the code COLLTYP but must appear as the first variable in the set. The few changes in the MINSUN variables take place in the subroutine MINSUB2.FOR at the end of the FKT routine. Successive variable sets are written with the first record of each set specifying the number of variable names to follow.

Subroutines:

VARMAT This subroutine is called once at the beginning of each MINREP run and whenever a new output variable set is to be processed. Its purpose is to match the variables specified in MINREP.VAR to the correct member of a long array consisting of basically all input and output variables of potential interest from MINSUN. At the end of the subroutine the headings of the MINREP output file are written - the first line is the variable Fortran name, the second is the correct units.

MINSUB2 This subroutine is a revised version of the original MINSUN. The optimization routine has been dropped and for each run FKT(3) and then FKT(5) are called. FKT(3) reads in the parameter input file and the collector input file. On successive runs with the same collector type, the program flow skips over the collector file read routine. FKT(5) then performs the system simulation and determines all the MINSUN output file variables. All the WRITE statements for the normal MINSUN output file have been commented out except those indicating errors. The other MINSUN output file (on Unit 8) is not written. MINSUB2 and MINREP share the COMMON block /MINREP/ which contains an array B(225). At the end of FKT(5) all B variables are set equal to the corresponding MINSUN variable (215 slots are currently used). Programming problems were encountered when a COMMON block in MINSUB2 consisting of the MINSUN variables was written to correspond to the B array defined in the same COMMON block name in the MINREP (calling) program, though this is preferable in terms of eliminating the resulting long list of executable statements.

To make successive MINSUN simulation runs, MINREP frees the user from manually and repetitively editing the parameter input file, running MINSUN, and then scanning each output file separately for specific variables. MINREP facilitates running of BATCH jobs with series of variable changes and provides the user with neat lists of only pertinent data. Additional subroutines may be readily written to automatically iterate input parameters in a specified manner, and to perform calculations on and plotting of the output file.