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HOW ENVIRONMENTAL CONSIDERATIONS ARE CHANGING THE CONSTRUCTION INDUSTRY: FIVE TECHNOLOGIES FOR LOWER ENERGY DEMAND AND DECREASED AIR EMISSIONS

By

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ABSTRACT

This thesis analyzes changes in the construction industry due to increased concern for the environment. The focus is on emerging energy-efficient technologies for cooling and heating that can reduce the air emissions from the production and consumption of energy.

The thesis investigates five technologies: energy-efficient building design and life-cycle costing techniques; ground source heat pumps; chill storage systems; phase changing materials for heat storage; and mined-natural gas storage. The thesis investigates these technologies by analyzing the latest developments of the technologies; the current and future markets for the technologies; the strategic attractiveness of the markets for these technologies to the construction industry; the investments required to enter the markets for these technologies ; and several applications of the technologies.

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Chapter 1: Introduction

1.1. The Consortium on the Construction Industry and Global Environment

The research for this thesis was conducted as part of the ongoing efforts of the Consortium on the Construction Industry and Global Environment. The Consortium was formed at the Center for Construction Research and Education in the Civil and Environmental Engineering Department at the Massachusetts Institute of Technology in January of 1991. The Consortium's mission is to: (1) identify opportunities for the construction industry in the area of the environment, (2) determine how these opportunities are (or will be) shaped, and (3) determine how to capitalize on these opportunities. [1]

Three initial reports by Prof. Nazli Choucri and Edmund S. Pendleton of MIT were the basis for further research by the Consortium. The first report by Prof. Choucri defined the broad issues for the construction industry due to new paradigms for economic growth which account for environmental concerns. Mr. Pendleton identified three major market opportunities for the construction industry for further research. These market opportunities can be broadly defined as: hazardous waste; solid waste; and the reduction of airborne pollutants from the production and consumption of energy. Waste water treatment was also identified by the Consortium as being an area of significant opportunity because of its close association with environmental quality.

Following the research which resulted in these first three reports, the Consortium began a process for identifying and evaluating specific technologies in these four markets areas for possible further research.

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[1] *Working Paper No. 4,* The Global Environment and Construction Industry Consortium, p. 1.

1.2. Rationale and Methodology for Technology Selection in the Energy Area

This thesis is the result of evaluating five technologies related to the reduction of airborne wastes caused by the production and consumption of energy. The preliminary work which led to the eventual selection of five technologies for further evaluation consisted of three steps. These were:

1. Identify the latest technologies being developed and used in this target area that were of particular interest to the construction industry.

2. Develop a standardized methodology for systematically evaluating and ranking the different technologies.

3. Make a final selection of five technologies in this area using both subjective and objective criterion.

The "long" list of technologies in the energy area was compiled through literature searches, database searches and interviews with technical experts. Technologies were only considered after an initial evaluation determined they should be considered by members of the construction industry as being within their areas of core competency. For example, CO_2 sequestering technologies were considered but reducing emissions from internal combustion engines were not.

Step 2 of the selection process involved evaluating the technologies using a framework which considered five general criteria. The general criteria were: current market size for the technology; the market suitability of the technology for the construction industry; the regulatory and social acceptability of the technology; the time to maturity of the technology; and the investment costs of the technology. The general criteria were further divided into 15 sub-criteria which were weighted by the researchers after consensus was reached on their importance. The technologies were then graded according to each of the sub-criteria and assigned a value between one and five. Five is considered "very favorable" and one is considered "unfavorable."

The result of the framework evaluation was a hierarchical list of technologies that were then further evaluated by the Consortium members using less objective measures. The final technologies chosen in the "energy" area for further research were: energy efficient building design and life-cycle costing techniques; ground source heat pumps; chill storage systems; phase changing materials for heat storage; and mined-natural gas storage.

In some cases, the technologies that were chosen by the Consortium members were also high in the evaluation framework ranking. In other cases, the technologies chosen were more a reflection of the Consortium members desire to investigate opportunities in markets where they were already established. In general, the technologies chosen for further research were related to increasing the energy efficiency in commercial buildings.

Chill storage and ground source heat pumps are both promising technologies for changing the energy consumption characteristics of commercial buildings. Phase changing materials is considered less promising but still potentially useful for the same reason. Energy efficient building design and life-cycle costing techniques are more methods or systems approaches to energy conservation in buildings than specific technologies. However as methodology or approach to building design, they are applied with the same purpose of increasing the total energy efficiency of buildings and lessening their environmental impact. Mined-natural gas storage is of particular interest in Japan and the Scandinavian countries where no naturally-occurring storage formations exist but where natural gas use is expected to increase significantly in the future. Finally, all the building-related technologies have the common characteristic that they can significantly reduce the consumption of energy in buildings which would then reduce airborne pollution emissions from power generating plants.

1.3. The Methodology for Technology Evaluation Used in This Thesis

A standardized format was developed for analyzing each technology in the thesis. Each analysis consists of an introduction followed by a section which describes the technology including its effectiveness, problems, patent status, and any prominent organizations involved in the technology's development. Following sections describe the regulatory and social acceptability of the technology; the market characteristics of the technology; the technology's attractiveness to the construction industry; and the investments required to enter the market where the technology is used. When possible, each analysis also includes several case studies that involved an analysis of actual applications of the technology. These case studies were an important part of the technology's evaluation and they provide interesting evidence as to the true market potential of the technology.

In its entirety, each analysis provides a clear evaluation of the market potential of the technology to the construction industry. The reports summarize the technical developments of the technologies as well as many of the important social, political, and financial aspects of the technology. The case studies also provide valuable information for the analysis by identifying specific projects that allow for further evaluation of the technology.

1.4. Overview of Chapters

Chapter Two of this thesis presents an analysis of energy efficient building designs and life-cycle costing methods. The analysis considers the use of techniques by building professionals for measuring a building's energy efficiency and environmental impact through life-cycle costing techniques. The analysis includes an evaluation of both the traditional life-cycle costing techniques developed by the American Society for Testing and Materials and newer techniques developed by the American Institute of Architects and others which consider environmental impacts and costs.

The research for chapter two concludes that a new design and construction approach which emphasizes energy efficiency and minimizing the environmental impact of buildings, has the potential for radically changing the nature of the construction industry. Firms that realize the potential of the market for increasing the energy efficiency of old and new buildings and that consider the environment far more carefully during the design process will gain competitive advantage in the next decade.

Chapter Three of this thesis is an analysis of ground source heat pumps. Ground source heat pumps are a well developed technology for using geothermal energy for heating and cooling residential buildings. The technology is gaining recognition as the most energy-efficient technology for heating and cooling commercial and residential buildings. As new applications in the United States increase in size and number, this technology is sure to gain more widespread recognition.

The conclusion reached in this thesis are that ground source heat pump technology is emerging as a technology with considerable potential for lowering the energy demands in commercial buildings that are currently being heated and cooled by conventional equipment. Construction and engineering firms with expertise in this technology will have the ability to compete effectively in providing their customers with the latest technology in the emerging markets for supplying energy-efficient systems for buildings.

Chapter Four of this thesis is an analysis of the market for using phase changing materials for heat storage in buildings. Phase changing materials (PCMs) such as salt hydrates or paraffins have been widely used for heat storage in conjunction with passive solar technologies for the last decade. New promising research in this area, involves adding PCMs to conventional building materials for widespread use in commercial and residential buildings.

The conclusions reached in this thesis indicates that if PCM can be added during the manufacturing process to conventional wallboard, then this technology will see more widespread application in both conventional and energy efficient buildings.

Chapter Five of this thesis is an analysis of the market for chill storage systems. Chill storage is the leading technology being utilized by the utility and construction industries for shifting electric power demand in commercial buildings for air conditioning from peak to off-peak hours. This technology is well established at this point. Ongoing research and development efforts aimed at increasing the efficiency of chill storage systems will greatly increase market opportunities supplying this technology.

The conclusions reached in this thesis are that construction and engineering firms must develop strategies for gaining expertise in this technology in-house or through alliances with system vendors and heating, ventilating and air-conditioning design firms. As utility expenditures increase on demand side management programs in the next decade, designing and constructing chill storage systems for both new and existing buildings will become a large and important market.

Chapter Six of this thesis is an analysis of the use of mined hard-rock caverns for natural gas storage and compressed air energy storage close to population centers of high peak demand. The technology is viewed as important because of the expected high future demand of clean burning natural gas. Most new power producing facilities will burn natural gas because they are less expensive to build and they easily meet new federal clean air regulations. The technology is of particular interest to countries like Japan, that lack naturally-occurring gas storage formations such as depleted gas wells or salt domes.

The conclusions reached in this thesis are that the technology may see increased use in the United States if regulations restrict the use of liquefied-natural gas plants in densely populated areas. The likelihood of the technology being applied is much higher in other countries with suitable hard-rock formations and no naturally-occurring storage sites.

Chapter 2: Energy-Efficient Building Design and Life-Cycle Costing Methods

2.1. Introduction

Increasing the energy efficiency of buildings represents one of the best opportunities for energy savings and efficiency in the United States (US) and in many other areas around the world. A wide range of technologies have been developed and introduced in the last two decades that can significantly improve the energy efficiency of buildings and lessen their environmental impact. These technologies include energy efficient heating, ventilating and air conditioning equipment (HVAC), variable speed motors and drives, energy efficient lighting systems, ground-source heat pumps, and chill storage systems.

Unfortunately, many of these energy-saving measures are added to existing buildings to improve the efficiency of only one or two systems within the building. In some new buildings, long lists of energy saving devices and systems are added in a discrete manner without designers and engineers taking a holistic view of the building with its future occupants. New studies indicate that substantially increased energy efficiency, lower initial costs, and significantly lower life-cycle costs (LCCs) can be the result of a more integrated approach to designing buildings for increased energy efficiency; worker productivity; and lower LCCs.

This chapter is the result of research into the latest trends and technological developments in the US on building energy-efficiency and using life-cycle costing methods to measure the impact of design decisions. The analysis will focus on the many different aspects of the building design and construction process that affect the LCCs of a building as well as the different methodologies that have developed for doing life-cycle analyses (LCAs).

The first part of the chapter will focus on current methodologies for applying LCCs methods to building design, construction and maintenance. The second part of the chapter will focus on new technologies in the US that impact many of the major components in the LCCs of a building including the initial construction costs, energy costs, worker productivity and a building's environmental impact. The third part of the chapter is case studies on new buildings in the US which are considered state-of-the-art in design for energy-efficiency, worker productivity, and low environmental impact.

2.2. Technology Description: Life-Cycle Costing Methods

Currently, there is a great deal of interest in life-cycle costing (LCC) and life-cycle analysis (LCA) in which environmental concerns are addressed. A major effort by different organizations has developed to standardize a methodology for doing LCAs that includes measures for calculating a cost for the impact of different products and processes on the environment. These organizations include the U.S. Environmental Protection Agency (EPA), the Society of Environmental Toxicology and Chemistry (SETAC), Audubon Society, and industry trade groups. These groups have agreed that a LCA is composed of three components: (1) *inventory analysis,* defined as a quantitative identification of energy and raw material requirements and waste generated at all stages of the life cycle; (2) *impact analysis,* which characterizes and assesses the ecological and human health impacts of the energy, resource and waste factors identified in the inventory: and (3) *improvement analysis,* which evaluates opportunities for prevention or reduction of environmental burden.[1] This represents a very broad scope for doing a LCA for a particular product especially for complex construction projects where thousands of different products are combined into a single product with a very long life-cycle.

This new expanded concept of a LCA is based on economic principles that have been developed for assessing the economic performance of different construction systems over a period of time. It is useful to analyze these more traditional methods because they are very important for understanding the economic implications of LCC and LCAs. Also, at some point in the future, qualitative information regarding the social and environmental costs of different building materials and methods will have to be defined in quantitative. Monetizing these environmental impacts in is complicated but once it has been done the costs can be put into the mathematical equations that have already been developed.

2.2.1. The Standard American Society of Testing and Materials Building Economic Evaluation Methods

Before focusing on the new expanded methodology of LCAs, it is necessary to describe the currently available methods for analyzing building economics.

Life-cycle costing methods in their purest form entail making standardized-cost calculations so that building design and construction professionals can make the most cost-effective choices when making building economic decisions. Dr. Harold Marshall and Ms. Rosalie R. Ruegg, two economists at the National Bureau of Standards in the US, have written extensively on building economics. Dr. Marshall and Ms. Ruegg developed

[1] *Environmental Resource Guide.* The Committee on the Environment, American Institute of Architects. Intro. VI. p. 2-3.

many of the current standards for the American Society of Testing and Materials (ASTM) and the US Government (USG) which are currently in use.

The ASTM has standardized several different methods for comparing the costs of alternative choices during the life of a building. These include the life-cycle cost method (LCC), the net benefit method (NB), the net savings method (NS), benefit-to-cost ratio (BCR), savings-to-investment ratio (SIR), internal rate of return (IRR), overall rate of return (ORR), discounted payback(DPB), and simple payback (SPB).[2] The mathematical equations for these methods are similar, but the information provided from the calculations and the purpose for using the different methods are quite different. Appendix 2.1. gives a brief recommendation of when the different methods should be used and what can be learned.

2.2.2. Life-Cycle Cost Method

The life-cycle cost method or a life-cycle analysis is probably the most well recognized method for evaluating the cost-effectiveness of different building projects. Environmental considerations and environmental groups have given a new meaning to the term by broadening the definition of the life of a project to include a "cradle-to-grave" definition of the life of a system or product. This issue will be addressed in greater depth later in this chapter. For now, the narrower definition of the term "life-cycle method" will be discussed, which will serve as the framework for later expansion of the definition.

ASTM Designation: E 917-89 the *Standard Practice for Measuring Life-Cycle Costs for Buildings and Building Systems,* "conceptually defines the computation of an LCC in present-value terms (*PVLCC*) as:[3]

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[2]Rosalie T. Ruegg, Dr. Harold E. Marshall. *Building Economics: Theory and Practice*. New York, New York: Van Nostrand Reinhold, 1990, p. 13.
[3]American Society for Testing and Materials (ASTM) *Standard Practice for Measuring Life-Cycle Costs of Building and Building Systems.* E 833-92. p. 770.

$$PVLCC = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \qquad (1)$$

C_t = the sum of all relevant costs occurring in year t
n = length of study period, years, and
i = the discount rate

Costs estimates for different alternatives should include estimates of the initial investments for the project including: equipment, engineering and labor, time dependent energy costs, non-fuel operation and maintenance, repairs and replacements, and the resale/scrap value of the equipment at the end of its useful life.[4] Another commonly used equation for calculating the *PVLCC*[5] is:

$$PVLCC_{A1} = Ip + Ep + Mp + Rp - Sp \qquad (2)$$

Ip = present value investment costs of alternative A1
Ep = present value energy costs associated with alternative A1
Mp = present value non fuel operating and maintenance costs associated with alternative A1,
Rp = present value repair and replacement costs associated with alternative A1,
Sp = present value resale (or scrap or salvage value) less disposal costs associated with alternative A1.

The most useful applications for the use of the LCC method is in making decisions related to the cost-effectiveness of various building decisions. A LCC calculation allows for accept/reject decisions based on cost calculations of various alternatives compared with a "do nothing" scenario. The method can be applied to situations where it is desirable to make the most cost-effective choice of various interdependent projects; deciding whether to lease or purchase buildings; deciding on investments to lower building costs; or any number of building related decisions which require long-term cost analysis.

ASTM E 917-89 systematically prescribes the discounting procedure for calculating the "present value" of the different cost categories. It is expected

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[4]Rosalie T. Ruegg, Dr. Harold E. Marshall. *Building Economics: Theory and Practice.* New York, New York: Van Nostrand Reinhold, 1990, p. 19.
[5]Ibid., p. 20.

that the cost of some items will change over time while others might be a fixed amount each year. The different scenarios require different discounting methods to maintain the integrity of the LCC analysis. ASTM E 917-89 defines the different discounting methods as well as different scenarios where they might be applied (see Appendix 2.2.). ASTM E 917-89 also outlines the method for adjusting *PV LCC* for income taxes, which can be important because of the tax implications of many building energy related decisions.

The ASTM standard for measuring LCCs also suggests how to make decisions after the LCC calculations have been made. The standards also suggest methods for including risk assessment into the decision as well as unquantifiable aspects of different design alternatives. ASTM E 917-89 states that:

> "A report of an LCC analysis should state the objective, the constraints, the alternatives considered, the key assumptions and data, the present-value or annual-value, or both of each cost category, and the total present-value or annual-value LCC, or both, of each alternative. Items whose values should be made explicit include the discount rate; the study period; the main categories of cost data, including initial costs, recurring and nonrecurring costs, and resale values; grants; tax deductibles; credits and expenses; and financing terms if integral to the decision-making process. The tax status of the investor should be given. The method of treating inflation should be stated. Assumptions or costs that have a high degree of uncertainty and are likely to have a significant impact on the results of the analysis should be specified and the sensitivity of the results to these assumptions or data described. Any significant effects that remain unquantified should be described in the report."[6]
>
> (for a description of "present value" and "annual present value" see ASTM E833-92)

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[6]American Society for Testing and Materials (ASTM) *Standard Practice for Measuring Life-Cycle Costs of Building and Building Systems.* E 917-89. p. 775.

2.2.3. Net Benefit Method

ASTM E 1074 - 91 the *Standard Practice for Measuring Net Benefits for Investments in Buildings and Building Systems* is another popular method for calculating economic performance over a given period of time of different possible investments.

> "The NB (Net Benefits) method, sometimes called the net present value method, calculates the difference between discounted benefits (or savings) and discounted costs as a measure of the cost effectiveness of a project. The NB method is used to decide if a project is cost effective (net benefits greater than zero) or which size or design competing for a given purpose is most cost effective (the one with the greatest net benefits)."[7]

The equation for the present value of net benefits (PVNB) is:

$$PVNB = \sum_{t=0}^{N} \left(B_t - \overline{C_t}\right) / (1+i)^t$$

where:
B_t = dollar value of benefits in period t for the building or system being evaluated less the counterpart benefits in period t for the mutually exclusive alternative against which it is being compared,
$\overline{C_t}$ = dollar costs, including investment costs, in period t for the building or system being evaluated, less the counterpart costs in period t for the mutually exclusive alternative against which it is being compared,
N = number of discounting time periods in the study period, and
i = the discount rate per time period.

2.2.4. Benefit-to-Cost and Savings-to-Investment Ratios

ASTM E 964-89[8], *Standard Practice for Measuring Benefit-to-Cost and Savings-to-Investment Ratios for Buildings and Building Systems* are two alternative methods for making economic evaluations of different possible choices over a period of time.

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[7]American Society for testing and Materials (ASTM) *Standard Practice for Measuring Net Benefits for Investments in Buildings and Building Systems.* E 1074-91. p. 881.

[8]American Society for testing and Materials (ASTM) *Standard Practice for Measuring Benefit-to-Cost and Savings-to-Investment Ratios for Buildings and Building Decisions.* E 964-89

"The BCR (Benefit-to-Cost Ratio) is used when the focus is on benefits (that is, advantages measured in dollars) relative to project costs. The SIR, (savings-to-investment ratio) a variation of the BCR, is used when the focus is on project savings (that is cost reductions) relative to project costs."[9]

The equation for the BCR is:

$$BCR = \frac{\sum_{t=0}^{N} \left(B_t - \overline{C}_t\right) / (1+i)^t}{\sum_{t=0}^{N} \overline{I}_t / (1+i)^t} \tag{4}$$

where:
BCR = benefit-to-cost ratio
B_t = benefits in period t; that is, advantages in revenue or performance, measured in dollars, of the building or system as compared with a mutually exclusive alternative,
$\overline{C}_t$ = costs in period t, excluding investment costs that are to be placed in the denominator for the building or system, less counterpart costs in period t for a mutually exclusive alternative,
$\overline{I}_t$ = those investment costs in period t on which the investor wishes to maximize the return, less similar investment costs in period t for a mutually exclusive alternative, and
i = the discount rate.

Note 1- Mutually exclusive alternatives are those for which accepting one automatically means not accepting the others. For a given project one mutually exclusive alternative may be not to undertake the project. If so, it is against this alternative that a potential investment must be compared to determine its cost-effectiveness. Alternative designs and sizes of a project for a given application are also mutually exclusive.[10]

The equation for the SIR is:

$$SIR = \frac{\sum_{t=0}^{N} S_t / (1+i)^t}{\sum_{t=0}^{N} \overline{I}_t / (1+i)^t} \tag{5}$$

where:

SIR = savings-to-investment ratio, and

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[9]Ibid., p. 821.
[10]Ibid., p. 823.

S_t = cost savings in period t, adjusted to include any benefits in period t, for the building or building system to be evaluated.

That is:

$$\sum_{t=0}^{N} S_t = \sum_{t=0}^{N} \left(B_t - \overline{C}_t\right) / (1+i)^t \qquad (6)$$

where:

$$\left|\sum_{t=0}^{N} \overline{C}_t\right| >> \sum_{t=0}^{N} B_t \qquad and \qquad \sum_{t=0}^{N} \overline{C}_t < 0$$

Note 2 - The BCR is normally used instead of the SIR unless cost reductions are *much* greater than revenue and performance advantages; hence the use of the symbol >> in the definition of S_t.

An alternative formulation of the BCR is[11]:

$$BCR = \frac{NB + \left(\sum_{t=0}^{N} \overline{I}_t / (1+i)^t\right)}{\sum_{t=0}^{N} \overline{I}_t / (1+i)^t} \qquad (7)$$

where:
NB = net benefits, and

$$NB = NB = \sum_{t=0}^{N} \left(B_t - \overline{C}_t - \overline{I}_t\right) / (1+i)^t \qquad (8)$$

The BCR and SIR results can be utilized for indicating the economic attractiveness of particular investments or for prioritizing different alternative investments according to their economic efficiency. ASTM E 964-89 outlines the particular applications that are well suited or poorly suited for applying the BCR and SIR methods. The methods are also suggested for:

> (1) accepting or rejecting individual investments; (2)choosing among nonmutually exclusive projects competing for a limited budget; (3)Selecting among alternative engineering alternatives; and (4) allocating among projects of various design and size.[12]

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[11]Ibid., p. 824.
[12]Ibid., p. 826.

2.2.5. Internal Rates of Return

ASTM E 1057 - 85 the *Standard Practice for Measuring Internal Rates of Return for Investments in Buildings and Building Systems* is another method for evaluating an investment over a given period of time. According to the ASTM:

> "The IRR (Internal Rate of Return) provides the compound rate of interest that equates the stream of dollar benefits over some defined study period. If that calculated rate of interest is greater than the investor's minimum accepted rate of return (MARR), the investment is considered economically attractive.
>
> The IRR is used to determine if a given project is cost effective, to compare the relative cost effectiveness of different purpose projects competing for a limited budget, and when calculated on incremental changes in benefits and costs, to evaluate which size or design for a given purpose is most cost effective."[13]

The IRR is "the compound rate of interest that, when used to discount a project's cash flow will reduce the present value of net benefits (PVNB) to zero."[14] An equation for the IRR (unadjusted) is:

$$\sum_{t=1}^{N}\left[\frac{B_t - C_t}{(l+i)^t}\right] - C_0 = 0 \qquad (9)$$

where:
B_t = dollar value of benefits (including savings and resale values) in time t,
C_t = dollar value of costs in time t,
C_0 = initial project costs as of the beginning of the base time, and
i = the rate of interest that discounts net cash flows to zero.

The "unadjusted" IRR equation is used for situations where net cash flows are reinvested at the same rate as that earned on the original investment. For situations where net cash flows are readjusted at a different rate than those earned on the original investment then the following equation should be used.

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[13]American Society for Testing and Materials (ASTM), *Standard Practice for Measuring Internal Rates of Return for Investments in Buildings and Building Systems.* E 1057 - 85.
[14]Ibid., p. 875.

$$\frac{\sum_{t=1}^{N}(B_t - C_t)(1+r_t)^{N-t}}{(1+i)^N} - C_0 = 0 \qquad (10)$$

where:
r_t = prescribed rate of return on reinvestment of cash flows realized in year t, and other variables are the same as in equation 9.

2.2.6. The Broadening Definition of Life-Cycle Costing Analyses

The ASTM standards that have been described previously are sufficient for many of today's building designers, engineers, and owners for analyzing the economic performance of alternative building systems over a given period of time. Unfortunately, there are many organizations that are interested in measuring and comparing the effects of different buildings and building systems using a cradle-to-grave approach to the LCC calculations or LCA.

The LCA approach is of particular importance in meeting the increasing number of environmental challenges that confront the building industry. Using the LCA approach has become the primary method for dealing objectively with the increasing emphasis society has placed on meeting environmental objectives. LCAs gives decision makers in government and the marketplace a tool for assessing the total environmental impact of different products and projects. The hope is that these impacts can then be minimized through informed decision making.[15]

Another aspect of looking at the total LCCs of a building is that it gives the owners, designers, and builders a new perspective on the financial implications of their decisions. Routine maintenance costs and initial construction costs are quickly overshadowed by energy and fuel costs; the salaries of workers in the building; and the financial and strategic

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[15]F. R. Field III, J. A. Isaacs, and J. P. Clark, *Life Cycle Analysis and Its Role in Product and Process Development.* Presented at the 2nd International Congress on Environmentally Conscious Manufacturing, August 29 - September 1, 1993, Key Bridge Marriot, Arlington, Virginia, USA

implications of the building on the competitiveness of the company. It is becoming increasingly apparent to decision makers in the building process that a life-cycle approach to constructing and maintaining a building needs to be used to minimize the environmental impact of buildings and, more importantly to many, to maximize the financial performance of the building and its occupants.

2.2.7. An Environmentalist's Approach to Life-Cycle Costing Analyses

A large number of groups including trade associations, government organizations, and environmental groups have developed methodologies for analyzing the LCCs of buildings. It is obviously a complicated task considering the hundreds of variables involved in the decisions and the difficulty of trying to quantify the environmental impact of different decisions. A somewhat simplified outline of the five phases of the building process is (see Appendix 2.3.):[16]

Phase 1 This represents mining and the transportation of raw materials and primary energy.

Phase 2 Manufacturing process, here called production. Waste production and pollution flows are also indicated, including those of the proceeding and following phases. Furthermore, an input flow of components manufactured and assembled elsewhere, is shown. The throughput of phase 2 is divided into two flows: one to increase and/or replace the building stock, and the other to maintain the existing stock during its service life.

Phase 3 This is the building activity itself. The throughput flow comes from the proceeding phases and can be smaller if the indicated input flow from re-usable components is bigger.

Phase 4 This is the service lifespan. Efforts to maintain the building during this period are indicated by a number of input flows. Technically speaking a more durable building needs less repair work and materials to keep the structure in good condition. However, in order to prevent loss of function,

[16]P.C.F. Bekker, *A Life-Cycle Approach in Building.* Building and Environment, Vol. 17. No. 1, pp. 55-61, 1982.

periodic upgrading to revised standards will be necessary. The latter is known as renovation, a process which is very important in maintaining the object in question.

Phase 5 After a period of decay, a building's life comes to an end. As a result of demolition three output flows arise. The biggest flow is rubble, which causes problems because of dumping limitations. We must realize that the present amount of demolition waste was produced five to 100 years ago and more. At that time the output of the building industry was much smaller than at present and the structures were much easier to demolish. Since reinforced concrete and high-rise buildings have been introduced it is much more complicated and expensive to modify a construction to revised standards and also to demolish it at the end of the service lifespan.[17]

The problem with models such as this is that they oversimplify the problem of determining the environmental impact of different design and construction decisions over the life-cycle of a building. However, they do represent a radical departure from the prevalent method in the construction industry of looking at a few simple variables such as initial costs, maintenance costs, and energy costs of different design decisions. They also represent a significant expansion of the methodology expressed in the ASTM standards for measuring the economic performance of different building systems. Although as previously stated the ASTM equations are applicable when costs and benefits can be monetized.

2.2.8. Life-Cycle Costing and The American Institute of Architects

The American Institute of Architects (AIA) has developed *The Environmental Resource Guide* (ERG) as parts of its attempt at promoting and contributing to a sustainable society. The AIA has approved *Five Actions In Support of the Environment.*[18]

Action No. 1. *Maximize your clients participation in all utility rebate/incentive programs.*

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[17]Ibid., p. 55-56.

[18]*Environmental Resource Guide.* The Committee on the Environment, American Institute of Architects. Intro. III. p. 1.

Action No. 2. *Immediately stop specifying any cooling system that contains a refrigerant with CFCs.*

Action No. 3. *Provide leadership to the building team through your active support of total energy support and life-cycle as an essential methodology. (Your findings analysis in most cases will support energy efficiency beyond building code requirements.)*

Action No. 4 *Endeavor to specify woods you know to be the product of "sustainable forests," those that are in continuing cycle of growth, management and harvest.*

Action No. 5 *Meet or exceed ASHRAE* (American Society of Heating Refrigeration and Air Conditioning Engineers) *'90 Standards for outside air in all projects you undertake (approximately 20 cfm per person).*

The AIA recognizes the significant impact that buildings currently have on the environment and the important part that architects can and must play in reducing that impact in the future. The ERG "is designed to help architects select the most environmentally sympathetic materials, specify the most efficient energy sources, plan sites in the most environmentally sound manner, and consider conservation and recycling during all phases of the project."[19] The AIA is careful to distinguish the difference between the information it has presented in the ERG and the information presented by the authors of various LCA although they consider the results of their work to be very important steps towards developing LCAs. The ERG methodology is different than a Life Cycle Assessment (LCA) in several important areas which are; the ERG includes quantitative and qualitative information where a LCA inventory emphasizes quantification; the ERG uses best available data that is not always complete while a LCA analysis is far more extensive and rigorous; the ERG constructs and uses general flow diagrams where the LCA is considered far more specific.

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[19]Ibid., Introduction.

The ERG contains flow diagrams which summarize much of the currently available information "on the major elements in the life cycle of each material."[20] (see Appendix 2.4.) The AIA is more concerned with the effects of different products that are of the most concern to architects and building designers. Their primary considerations in developing their Life-cycle Inventories (LCI) information charts for different products were; "(1) natural resource depletion and ecosystem effects, (2) energy consumption, (3) waste generation, and (4) indoor air pollution. The AIA makes quite clear their intention is to focus on those environmental considerations that are most important to architects. The organization recognizes the complexity of undertaking LCAs with a broad scope and the time and costs they would entail.[21]

Unfortunately, the ERG lacks quantitative data that might be useful in developing environmental costs scenarios that could then be used in the ASTM equations presented earlier in this report. Although some organizations have tried to assess the environmental costs to society of some common pollutants, the AIA has avoided doing this for a variety of reasons. This is understandable given the complexity of the task, but at some point in the future it will need to be done to make their life-cycle summary more useful.

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[20]Ibid., Intro. VI. p. 4.
[21]Ibid., Intro. VI. p. 4.

2.2.9. The Difficulties Associated with Doing A Life-Cycle Analysis

The reluctance of the AIA to move beyond the *inventory analysis* stage of an LCA can be seen in many different industries as the complexity of developing an *impact analysis* and an *improvement analysis* is recognized. The results of research currently being done at the MIT Materials Systems Laboratory (MSL) on LCA identifies the potential difficulties of the later stages of an analysis. The difficulties the MSL has identified are considerable and they point out the fundamental weakness that LCC methods have when they are applied incorrectly in evaluating environmental issues.

If the intent of LCA is to give the practitioner an understanding of the environmental impact of various potential alternatives, then first the environmental impact of each alternative has to be measured, and secondly, the alternative with the least impact for a particular group needs to be chosen. The first task of evaluating the total environmental impact of different alternatives is daunting. If the inter-relatedness of different pollutants are considered then the task becomes almost impossible given the current level of scientific knowledge in this area. Once the impacts of different alternatives have been measured it becomes simpler to reject alternatives that have significantly higher environmental impacts than others.[22]

These alternatives are called the "dominated set" and they can be easily rejected because their exclusion "reduces all environmental impact" of the product or project.[23] The real difficulty comes in deciding among the remaining alternatives, the "non-dominated alternatives." These are never better than all the other alternatives in all respects.

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[22] F. R. Field III, J. A. Isaacs, and J. P. Clark, *Life Cycle Analysis and Its Role in Product and Process Development.* Presented at the 2nd International Congress on Environmentally Conscious Manufacturing, August 29 - September 1, 1993, Key Bridge Marriot Hotel, Arlington, Virginia, USA. p. 3.
[23] Ibid., p. 3.

The decision making process between "non-dominated alternatives" is one of the most difficult aspects of developing environmental policies and it has not been made any easier by the use of LCAs. However, in order to develop an "improvement analysis" the decisions need to be made. In developing the "improvement analysis," the decisionmakers must apply some value judgment regarding the alternatives that protects their own strategic interests. Since the decisions made during the "improvement analysis" reflect the values of the decisionmaker and not necessarily the values of society at large, there is the potential for major conflict during this stage. The MSL research takes note of the difficulties in applying value functions or judgments to environmental considerations in trying to develop group preferences for different alternatives. The two main reasons are:[24]

1. In order to choose between two or more alternatives, the implications of the choice must be fully understood. Otherwise the choice is meaningless and essentially random. When experts cannot establish what the incremental of the potential changes in environmental release and resource consumption represented by two alternatives is, it is virtually impossible to expect these experts not to mention the public at large, to say that one is preferable to the other.

2. Even if all the implications of each choice were completely characterized to the complete satisfaction of all members of the group, there remains the fact that individuals do not have a consistent set of objectives when confronted with environmental choices. For example, some may believe preventing global warming is more important than reducing urban air pollution, while others believe that neither of these objectives is as important as maintaining and improving human health. This lack of a consistent set of priorities in the environmental area essentially eliminates the possibility that a useful value function could be constructed.

These considerations highlight the difficulty of progressing from the "inventory analysis" portion of a LCA to the "impact" and "improvement analysis" if the eventual expectation is that a single alternative with the

[24]Ibid., p. 5.

lowest environmental impact will become apparent. Given the complexity of these issues, it is highly unlikely that a careful LCA of a product as complex as a commercial or industrial building will result in a single alternative that is the best alternative for everyone involved. What is more likely, is that the LCA will force decision makers to view each alternative in different ways and provide a tool for making better, more informed decisions.[25]

2.2.10. A More Realistic Approach to Life-Cycle Analysis

The effect of the current interest in the life-cycle of buildings has been an awareness among many design and building professionals that a new set of priorities needs to be developed to guide the design and construction process. These priorities are necessary so that decisions can be made which more closely reflect the importance of the decisions to the life-cycle costs of the building to society, the owner, and the occupants of the building. Even though final decisions will reflect the strategic interests of the decisionmaker as stated earlier in this report, at least there will be an awareness of the LCC implications of different alternatives. Since the environmental considerations of decisions are becoming increasingly important to society and the building's occupants, these concerns need to be reflected in the LCA.

In the US the implications of doing LCA on buildings has been a renewed focus on the environmental impact of buildings; increased demand for energy conservation in buildings; and an increasing awareness that employee productivity and welfare is of paramount importance to the prosperity of a business and it should be enhanced by the building.

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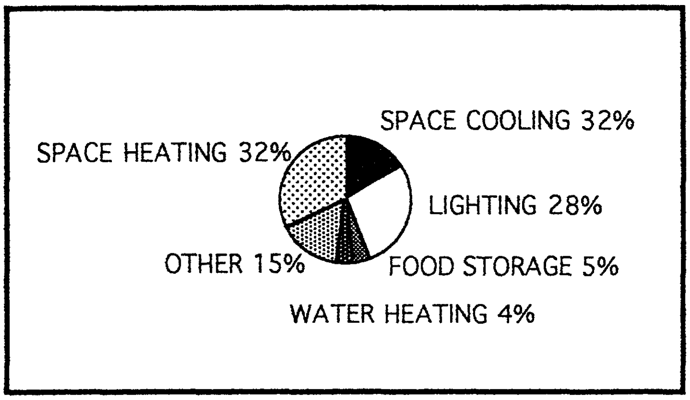
[25]Ibid., p. 6.

2.2.11. Energy Conservation Measures for Commercial Buildings in the US

There are encouraging trends in the US regarding the energy consumption in commercial buildings. The first of these is that while the total square footage of commercial buildings has increased significantly from 1970 to 1990 while the consumption of energy per square foot has remained constant. This is despite a dramatic increase in the use of air conditioning and electronic office equipment. (see Exhibit 2.1.)

Exhibit 2.1. US Commercial Building Sector Energy Use by End Use



Source: Office of Technology Assessment, *Building Energy Efficiency,* p. 22.

Increasing the energy efficiency of US commercial buildings has involved examining many different options in each of the buildings major systems. (see Appendix 2.6.) Considerable improvement has been made in improving the energy efficiency of commercial buildings in the US but unfortunately, they still lag far behind buildings in other countries of the developed world. Part of this is due to the relatively low cost of fuel and to the lack of incentives for property owners in the US to invest in energy saving measures that would only benefit their tenants. These and other structural barriers to increased energy efficiency, are well documented while fortunately energy efficiency has improved despite them.

New regulations, government policies, and utility incentives should help to continue this improvement. There are encouraging examples in the US which are discussed in the case studies of this chapter, that show that it is possible to cut energy consumption by as much as 70% on new and existing buildings using currently available technology. However, the major focus in the US has been on achieving more modest gains by improving the energy efficiency of the HVAC system; mitigating any potential ill effects this may cause on the occupants of the buildings; improving the energy efficiency of the lighting systems in existing buildings; and improving the productivity of employees in the building with new workstation designs. The economic benefits of these savings are substantial when analyzed over the life-cycle of a

building. It is also hoped that the increasing number of examples of buildings with low LCCs will provide enough information to skeptical design professionals that this trend will continue.

2.2.12. Energy Efficiency, Indoor Air Quality, and Employee Productivity

According to David P. Wynon, a leading expert on the health and productivity effects of buildings:

> "buildings are climate transformers: they process the raw material available outdoors-heat, cold, noise, light, air, and water with various unwanted additives-in such a way that the final product is suitable for the human activities to be performed indoors. This may be said to be the contribution of buildings to the productive process."[26]

This view of buildings as contributors to the production process represents a recent acknowledgment on the part of building professionals that

[26]David P. Wynon, *Healthy Buildings and Their Impact On Productivity,* National Swedish Institute for Building Research, Gavle, Sweden. Introduction.

buildings are of strategic importance to a business and that they can have a significant impact on the productivity of employees working in the building. Research indicates that efforts to lower the building related components of the LCCs, initial costs, energy, maintenance, etc., may significantly effect the occupant related components, salaries, productivity, and healthcare costs, etc., of the LCCs of a building. Conversely, there now exists the opportunity during the design and construction process to significantly lower building related LCCs and to positively increase employee productivity as evidenced by the buildings analyzed in the case studies.

Unfortunately, the evidence indicates that attempts over the last two decades at lowering energy costs may have significantly increased the incidence of sick building syndrome (SBS) and inadvertently raised the occupant related components of building LCCs. Fortunately, this fact has been recognized and the new emphasis during the design process is on using the best building system components to improve the thermal, air, acoustic, visual, and spatial quality of a building to enhance the building's integrity.[27] This shift is taking place because of the increased awareness that buildings and their occupants must be treated as integral parts of a complex system in order for the lowest LCCs of a business to be realized.

Much of the increased awareness of the relationship between a building and its occupants is the result of research into the effects of indoor air quality (IAQ) on worker productivity. Research indicates that:

> "When occupants are exposed to environmental conditions that may result in illness or discomfort, not only is their health at risk, but unnecessary costs may be incurred. If management decisions to decrease costs of energy, maintenance or other owning and operating costs result in decreases in productive attitudes and or concentration of the occupants, or increases in absenteeism or lost time, those decisions

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[27]Vivian Loftness, Volker Hartkopf, Peter A.D. Mill, *The Intelligent Office*, Progressive Architecture, September, 1990.

may be counterproductive to the occupants, employers, and building owners."[28]

This fact is especially significant considering that the World Health Organization estimates "that 30% of the buildings in the developed world may have problems that can lead to occupant complaints and illness."[29] (see Exhibit 2.2.) The National Institute for Occupational Safety and Health (NIOSH) conducted IAQ studies of 446 buildings and found that 50% of the problems were from inadequate ventilation and that some of the cases were exacerbated by energy-conserving measures.[30] The irony is that these energy savings amount to only 2% of the LCCs of operating a building.[31] Nearly 90% of the LCCs are salaries of the people working in the building. This fact highlights the stressors which include:[32]

- chemical and particulate contaminants in 75% of the cases
- odor discomfort in 70% of the cases
- thermal discomfort in 55% of the cases
- Microbiological contaminants in 45% of the cases
- nonthermal humidity problems in 30% of the cases

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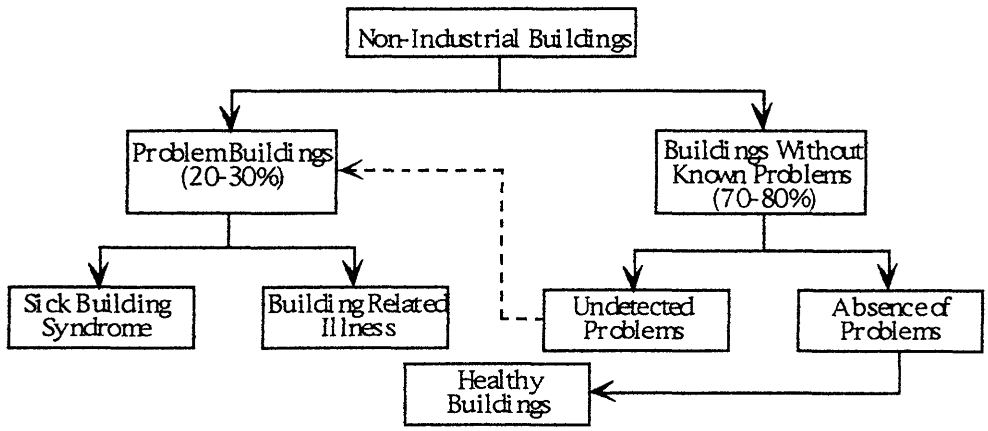
[28]James E. Woods, Ph.D., PE. *Cost Avoidance and Productivity in Owning and Operating Buildings,* Occupational Medicine: State of the Art Reviews, Vol. 4, No. 4, October-December 1989.
[29]Ibid., p. 754.
[30]John F. Hennesey III, P.E. *Engineering Challenges for the Environmental Decade,* Consulting/Specifying Engineer
[31]Anne Garvin, *The Intelligent Workplace,* The Construction Specifier, January, 1993 p. 36.
[32]Ibid., p. 756.

Exhibit 2.2. Populations of Non-Industrial Buildings

Two Environmental Populations of Non-Industrial Buildings



Source: B. Berglund, T. Lindvall, Proceedings of Healthy Buildings, 1988 Swedish Council for Building Research

Two studies citing the frequency of occurrence of the causes of these stressors are listed in exhibit 3. LCA indicate that the initial costs of a building represent only a small portion of the total costs of a building. The LCA also indicates the importance of considering design and operations factors in controlling IAQ so that the health of the occupants of the building are not adversely affected. Exhibit 2.3. shows the total percent that different types of problems occur in problem buildings. For example, "inadequate outdoor air" is evident in 75% of the problem buildings in the Woods study and 64% of the buildings in the Robertson study.

Exhibit 2.3. Physical Causes of Problem Buildings

FREQUENCIES OF OCCURRENCE OF PHYSICAL CAUSES OF PROBLEM BUILDINGS REPORTED BY TWO INDEPENDENT INVESTIGATIVE TEAMS: WOODS AND ROBERTSON			
		Frequency of Occurrence	
Problem Category	Physical Cause	Woods	Robertson
	System Problems		
Design	Inadequate outdoor air	75	64
	Inadequate air distribution to occupied spaces (supply and return devices)	75	46
	Equipment Problems		
	Inadequate filtration of supply air	65	57
	Inadequate drain lines and drain plans	60	63
	Contaminated ductwork or duct linings	45	38
	Malfunctioning humidifiers	20	16
Operations	Inappropriate control strategies	90	NA
	Inadequate maintenance	75	NA
	Thermal and contaminant load charges	60	NA

The importance of good IAQ, has not been missed by many building design professionals. More and more emphasis is being placed on the importance of giving building occupants individual control of the temperature, quantity, moisture, and velocity of the air in their immediate environment. This allows individuals with widely different requirements to have comfortable work environments instead of having to accept what is desirable for a majority of the building's occupants. A unique system developed By Johnson Controls that gives each occupant a high degree of control will be discussed in one of the case studies.

The AIA has called for significantly higher quantities of air per person than those called for under the ASHRAE standards. The AIA, as well as other organizations, has recognized that current ASHRAE standards may be inadequate for diluting nonhuman pollutants.[33] Additionally, the estimated cost of lost productivity and increased sick leaves of between 4.4 and 10 billion dollars has created enough concern in the US Congress that IAQ legislation seems imminent. Litigation will almost certainly increase as science establishes clearer links between indoor pollutants and ill health. All these factors reinforce earlier statements in this chapter that measures to lower the building related components of LCCs must now being carefully considered in the US for their effects on occupant health and productivity.

2.2.13. Energy Efficiency, Lighting, and Employee Productivity

Lighting in commercial buildings is another area where US building design professionals have focused their attention. The intent is to lower energy demand and to increase employee productivity over the life-cycle of the building. Since lighting accounts for 28% of the current energy consumption in US commercial buildings and 41 percent of the commercial electricity use, there is room for improvement.[34] 55% of lighting electricity in the commercial sector is consumed by fluorescent lamps. There is a huge potential for cost-effective energy savings by replacing this existing stock with new energy efficient flourescents.

The opportunity also exists to cut lighting-related energy use while improving worker productivity by substituting overhead flourescents with task-oriented lighting fixtures. Task lighting can be more effective and efficient while giving the occupant a higher level of control over the lighting in their immediate environment. Task lighting and various measures

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[33]Michael J. Hodgson, MD, MPH et al, *Symptoms and Microenvironmental Measures in Nonproblem Buildings,* Journal of Occupational Medicine/Volume 33 No. 4, April 1991. p. 527.
[34]U.S. Congress Office of Technology Assessment, *Building Energy Efficiency,* OTA-E-518, p. 54.

including new lamps, ballasts, reflectors, and fixtures can reduce energy costs by up to 37% according to an Energy Producers Research Institute (EPRI) study.[35] Better controls and improved building designs which use more natural light can also significantly improve their energy efficiency. All these lighting technologies are being actively promoted by the EPA as part of their successful "Green Lights Program."

In this program the EPA takes an active part in implementing lighting upgrades for large commercial users. The program is responsible for helping organize lighting surveys, utility rebates, and education efforts so that company personnel are better able to make decisions. Many or these programs have seen 20 to 40% post-tax returns on investments with improved lighting quality.[36]

2.2.14. Technology Content

2.2.14.1. Effectiveness

The effectiveness of energy efficient technologies in the US has been proven using many methods including LCA. The US Congress, Office of Technology Assessment (OTA) has estimated that the additional cost of many energy saving technologies can be paid back in less than seven years. The additional cost of energy efficient compact fluorescent lighting can be paid back in less than two years.[37] Improvements in building energy-efficiency which also positively effect the productivity of building occupants can have a far greater effect on lowering the LCCs of a building. Recent research indicates that many energy efficient technologies combined in a holistic fashion in new buildings and in retrofits of existing buildings are very

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[35]Ibid., p. 56.

[36]*Speaking with Bob Kwartin: Green Lights in Action, Implementing Effective and Efficient Lighting Retrofits.* Building, March 1993, p. 69.

[3737]U.S. Congress Office of Technology Assessment, *Building Energy Efficiency,* OTA-E-518, p. 4.

effective at lowering the LCCs of buildings and increasing employee productivity.

2.2.14.2. Problems

The problems, as mentioned earlier in this report, are that many energy conservation measures taken to lower the LCCs of buildings can adversely effect employee productivity. Lower LCCs related to the building may dramatically increase the LCCs related to the employees if a realistic assessment of productivity costs is included in the LCA. Since an estimated 90% of the LCCs of a building are related to the employees in the building, it is imperative that attempts to lower energy costs not lead to higher employee costs because of lower employee productivity.

2.2.14.3. Patent Status

Most of the energy-efficiency related technologies currently available in the US are protected by patents. The practices and procedures of measuring their effectiveness using a LCA is not covered by patents. Proprietary software, such as the computer-software program developed and sold by the ASTM, is usually covered by patents.

2.2.15. Research Groups, Companies, Organizations

Research on energy-efficiency related technologies and using LCC methods is being done by many US government agencies and building research centers including:

Rocky Mountain Institute
1739 Snowmass Creek Road
Snowmass Colorado 81654-9199
(303) 927-3851 FAX (303) 927-4178

Risk Reduction Laboratory
Office of Research & Development
US Environmental Protection Agency
Cincinnati, Ohio 45268

U.S. Congress Office of Technology Assessment
Washington, DC 20510
Energy and Materials Program
Phone # (202) 228-6286

American Institute of Architects
1735 New York Ave.
Washington, DC 20006
FAX (202) 626-7518

Lawrence Livemore Laboratories

American Society of Testing and Materials

US Department of Energy

2.2.16. Developing Technologies

Technologies to cost-effectively improve the energy efficiency of buildings are being developed continuously. New methods for measuring the effectiveness of these technologies using LCC techniques are also being developed. These include efforts by the DOE to develop models for measuring the energy use in buildings and computer programs by the ASTM. Many technologies have the potential for significantly lowering the LCCs of commercial buildings in the US.

2.3. Regulatory and Social Acceptability

2.3.1. Legal/Regulatory Acceptability

Minimum energy efficiency is enforced through the use of federal regulations and state and local building codes. Many state and federal programs also exist that help to overcome market barriers to increased energy efficiency. These include utility DSM programs and the EPA's "green lights program." It can be stated that legal and regulatory agencies in the US support increased energy efficiency and the use of LCC methods to measure their effectiveness.

2.3.1.1. Mandatory Technologies

Minimum energy efficiency is regulated in the construction of new buildings by local, state and federal building codes. These standards do not require the use of many energy-efficient technologies that could dramatically increase the energy-efficiency of commercial buildings. Using these technologies is usually decided by the building's owner and is not mandatory.

2.3.1.2. Permitting

Permitting for the use of energy-efficient technologies is not considered a problem in their use. Many of these products are improved versions of existing products that have been standardized in the construction industry for many years. A small percentage of new products that have been recently introduced as substitutes for less energy-efficient or environmentally unsound products, have had trouble meeting building code requirements.

2.3.2. Associated Liability

The associated liability of a contractor designing and building an energy-efficient building is limited. Many of the technologies and products are standard products that have been used for long periods of time. There are also many examples in the US and abroad where these technologies have been used successfully without the potential of future litigation. Some examples do exist however where actual energy savings did not match the level expected savings. These examples point out the need for detailed study of the design and occupant requirements to avoid potential liability. Many experts are also requiring a commissioning period after the building is completed so that systems can be tested and fine tuned. This process completes the design and construction cycle of a building and assures the different parties that all systems meet design specifications.

2.3.3. Public Acceptability

The public acceptability of energy-efficient technologies can be measured on two levels. The general public consensus is that energy efficiency should be increased for environmental and social reasons and that this public sentiment should be manifested in government action. The public has shown less willingness to support energy-efficient products by buying them in the marketplace. The public expects simple payback periods of two to three years on more expensive energy-efficient products which in many cases is unrealistic.

2.3.4. Political Acceptability

Political support for increased energy-efficiency is mixed in the US. There is political support for utility demand-side management (DSM) programs but many organizations believe much more political support is needed.

2.3.5. Related Public Health and Environmental Issues

Public health and the environment are two very significant issues related to increased energy-efficiency in commercial buildings. The environmental implications of increased energy-efficiency can be assessed using LCA methods. Although these analyses are quite controversial, few people deny that increased energy efficiency would significantly lower the LCCs of a building for society. However, as mentioned previously, increased energy efficiency should not come at the expense of lower IAQ. Higher net

LCCs may actually result after health and lower productivity costs are measured over the 45 year life-cycle of a building if an integrated approach to design and construction is not used in which all environmental and health related issues are incorporated.

2.4. Market Characteristics

2.4.1. Market Size: Present and Future

The market for modernizing all buildings in the US in 1993 is estimated at $71 billion dollars while an estimated $56 billion will be spent on new buildings.[38] Of the total, 62 percent will be spent on modernizing office buildings. (see Appendix 2.7.) A large percentage of these projects will include measures to increase the energy efficiency of the buildings. (see Appendix 2.8.) These figures indicate that the remodeling market in the US will be larger than the market for new construction while also indicating that increasing the energy efficiency of existing buildings is one of the primary purposes behind the remodeling effort.

2.4.2. Market Trends

The literature indicates that this trend towards increased energy-efficiency will continue. Utility spending on DSM programs is expected to increase significantly in the next five years as utilities change their focus from being energy producers to energy management companies. This spending will create a large market for energy-efficiency related construction. Building owners are also expected to increase spending on energy efficiency as part of facility upgrades; efforts to increase IAQ; and efforts to remain competitive in a slow economy.

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[38] *1993 Modernization Survey,* June 1993, p. 68.

2.4.3. Time to Commercialization

Many energy-efficient products are already commercially available. However, new designs such as the ones mentioned in the case studies are a recent trend.

2.4.4. Nature of Competition

The nature of the competition for the work on increasing the energy efficiency of US commercial buildings will be similar to the level of competition throughout the industry. Many of these projects such as lighting retrofits or energy management systems, can be provided and installed by existing contractors. Some new markets may develop, but it is very likely that they will be dominated by existing market players.

2.5. Market Attractiveness to Construction Industry

2.5.1. Strategic Attractiveness

For the purpose of discussion, the market under consideration is defined as "the market for energy efficient products and buildings in the US." A useful tool for analyzing the competitiveness or strategic attractiveness of an industry is Michael Porter's "five-forces model."[39] Porter's model determines the competitiveness of an industry by analyzing the power and impact of the five major forces that are at work in a market economy: "the threat of new entrants," the "bargaining power of suppliers," "the bargaining power of buyers," "the availability of substitutes," and "the intensity of rivalry" with industry competitors.

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[39] Porter, Michael E., *Competitive Advantage,* (New York, The Free Press, 1985)

The "threat of new entrants" is always high in any construction market in the US. The highly fragmented construction industry with low barriers to entry, means that it is difficult to defend a market position from new entrants. Since many of the products and services required to design, construct, or remodel a building for higher energy efficiency can be supplied by a large number of existing contractors, the "threat of new entrants" is considered high. This situation is considered unfavorable for the large construction/engineering firm already in this market.

The "bargaining power of suppliers" is considered low in the market for energy-efficient products and buildings. There exist enough substitutes and competing suppliers that free-market forces exist. Windows, insulation, HVAC systems, and designs can all be bought from competing suppliers using a low-cost or bid system of procurement. This makes the "bargaining power of suppliers" low which is considered favorable for a large construction/engineering firm in this market.

2.5.2. The "Bargaining Power of Buyers"

The current economic condition of the construction market and the overcapacity of the construction industry in the US have combined to create a very favorable situation for buyers of all construction services. This includes the market for energy-efficiency related products which are not so unique that they cannot be purchased using competitive bidding. This makes the "bargaining power of suppliers" high which is unfavorable to a large engineering/construction firm in this market.

Substitutes for energy-efficiency products can take a number of different forms. These forms include; direct substitutes of similar products from different manufactures; different products which have the same end result; or the option of doing nothing based on a LCA of the intended investment. There are hundreds of alternative products available from different manufacturers. There are also many different ways to increase the energy efficiency of buildings while quite often building owners simply do nothing because the payback period on an investment is too long or they lack funds. Design and construction services are also available from many competing firms for energy-efficient buildings. As a result, the "availability of substitutes" is high which is an unfavorable situation for any large engineering/construction firm in this market.

The "intensity of rivalry" within the US construction market is very high. The industry is very fragmented with local, regional, national, and international firms competing for most large jobs. The barriers to entry are low and regional markets are very difficult to defend. The market for energy-efficient buildings is not differentiated enough that most firms could not freely enter and exit the market as they do other construction markets. This makes the "intensity of rivalry" similar in the market for energy-efficient building construction and design to the "intensity of rivalry" in the general construction market. This is considered an unfavorable condition for the large engineering/construction firm in this market.

2.5.3. Cost-Effectiveness for Customers

The cost-effectiveness for customers of energy-efficient products and buildings has been discussed at length in earlier portions of this chapter. It is possible to calculate the cost effectiveness of these investments using a LCC method. Many of these investments have a simple payback period of between two and seven years on the additional cost versus a standard product. Experience is showing that buildings designed for energy efficiency can actually be less expensive because of the tradeoff between the cost of smaller

HVAC systems and more energy efficient windows, facades and mechanical equipment.

2.5.4. Suitability for Construction Industry for Planning, Design, Construction, and Maintenance of Energy-Efficient Buildings

The market for energy-efficient building construction and design is a construction market. Building design, engineering, and construction professionals are the most qualified personnel for doing work in this market. Their current expertise is well suited for implementing energy-efficient systems in new and existing buildings. However, they will have to include more outside expertise in the areas of human health, the environment, and worker productivity to meet the new objectives of building owners and environmentalists. For many companies acquiring the expertise in integrated design for minimizing LCCs is a logical expansion of their current expertise.

2.6. Investment Requirements

New investments required to enter the market for energy-efficient buildings will most likely be in the form professional training and education. Increasing the awareness of design professionals to the implications of their decisions to the LCCs of a building will take time and money. Many of today's design professionals have not been trained to think of the long-term effects of their decisions on human productivity, energy costs, and the strategic objectives of their clients. Effecting this change will take time and investments in training and education.

2.6.1. Research and Development Costs

Research and development (R&D) costs related to energy-efficient building design, construction, and new products has mostly been done by government organizations, universities, and manufacturers in the US. Little R&D has been done by large engineering/construction firms but it is not required to enter this market. The technologies currently available exceed the needs of the marketplace while new R&D efforts need to be focused on making them more cost-effective so they will be used more often.

2.6.2. Government Aid

Government aid from various federal agencies such as the DOE and the EPA is directed towards basic research on energy efficiency. Government regulations requiring DSM programs from utilities do not have a considerable impact on the energy-conservation market. However, direct government aid to contractors or building owners for implementing energy-conservation measures are not available except for a limited number of research-oriented projects. The US government appears to favor the use of free-market forces to accomplish their energy-efficiency objectives.

2.6.3. Capital Costs

The capital costs required to enter the market for designing and building energy-efficient buildings are similar to the capital costs for any large construction/engineering firm. These include the costs related to fixed assets and machinery required to execute any large construction job.

2.7. Case Study: The National Audubon Society Building

2.7.1. Introduction

The National Audubon Society (NAS) is America's most recognized environmental conservation non-profit organization. Their efforts are well thought of for representing the mainstream position of many Americans on different environmental issues. Originally, the organization focused its efforts on protecting birds and bird habitats but under a new president the organization has greatly expanded its conservation role. The Audubon society now routinely takes a position on most issues that have a significant environmental impact.

2.7.2. The National Audubon Approach

The NAS wanted to make a statement with its new headquarters regarding its commitment to the philosophies it espouses and to the viability of energy efficient, ecologically sound, and financially rewarding architecture. Their efforts to build an environmentally-sound new corporate headquarters have been rewarded with an example of "eco-sensitive architecture" that some say "sets a new national standard for an environmentally sensitive workplace."[40] The NAS developed a set of guidelines, soon to be published, for the development of their building very similar to those outlined in the American Institute of Architect's Natural Resource Guide.

The guidelines emphasize the use of an approach to building that includes a careful analysis of the life-cycle implications of the building and the materials used in the building. The Audubon used the expanded approach to performing a LCA that has been advocated for studying the impact of

[40]Donald Albrecht, *Urban Oasis,* Architecture, June, 1993. p. 62.

products and production on the environment. The NAS made a commitment to:[41]

1. Isolate the direct and indirect environmental problems associated with office buildings, and the building systems and practices from which they emanate.

2. Make design, purchase and management decisions to address the environmental impact of these systems and practices, balancing them always with practical cost considerations.

The primary focus of the NAS was on achieving high performance in the building in four areas: energy conservation, reduction of polluting gas emissions, resource conservation, and indoor air quality.

The success of the building is due in part to these well defined goals; a commitment to achieving them; and a willingness to use life-cycle costing methods for measuring the financial and environmental impact of alternative products and systems. These methods included the use of straightforward LCC methods advocated by the ASTM for analyzing lighting changes and higher quality windows, to the use of environmental guidelines on the choose of wood products only from renewable forests. Another example of the use of LCA that includes both financial and environmental considerations is the choice of a gas fired heating and cooling unit versus oil or electric. The NAS advocated burning gas because less airborne pollutants are emitted lowering the LCCs for society. The unit is also far more efficient which meant lower LCCs to the NAS for the building. The unit also contains no ozone-depleting CFCs which lowered the environmental costs of the unit while it was also less costly and less polluting than using conventional electric air conditioning equipment.

Another major factor in the success of the project was the architectural firm the Croxton Collaborative which had done several previous projects that

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[41]National Audubon Society, *Audubon Headquarters: Building for an Environmental Future*

were well recognized for their environmentally sensitive designs. The most well recognized of these projects was a new headquarters for the Natural Resources Defense Council (NRDC). The NRDC had similar requirements to the NAS and many of the current practices of the Croxton Collaborative were developed as part of that project.

2.7.3. The Building

One of the most environmentally sound decisions the NAS made was to purchase a dilapidated, but structurally sound building, at 700 Broadway in lower Manhattan. The building was designed by George Brown Post, the architect of the New York Stock Exchange, for use as a department store in 1891. The building is a "neo-Romanesque structure of glazed brick, terra-cotta, and cast iron,"[42] that contains many features which give it architectural integrity. This older building seems to fit the character of the NAS more closely than many of the newer buildings gracing New York's skyline that are built of glass and steel.

Purchasing this building also was consistent with the NAS guidelines of keeping the building affordable and maximizing the recycled content of the building. The Croxton Collaborative estimated that "recycling" the building preserved 300 tons of steel, 9,000 tons of masonry, and 560 tons of concrete. This approach also saved the expenditure of energy that would have been required during the life-cycle of the new building products as well as the landfill space required for disposal of the old ones. The purchase price of $10 million was only slightly more than the value of the land. The NAS estimated that retrofitting the old structure saved nearly $9 million in construction costs versus building a new structure with similar materials and specifications. This approach was so successful at meeting both their financial and recycling

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[42]Donald Albrecht, *Urban Oasis,* Architecture, June, 1993. p. 62.

goals that the NAS is encouraging the retrofitting of older buildings whenever possible as one of the lessons learned during the project.

2.7.4. Energy Conservation: Lighting

The NAS had two major guidelines regarding the energy efficiency of their new building. The first was that it be as energy efficient as possible using products and technologies that had been commercially available for at least one year. The second guideline was that the cost premium of the energy-efficient products versus standard products be recoverable within three to five years.

The major focus on improving the energy efficiency of the entire building was on improving the energy efficiency of the lighting system and the facade of the building. The approach taken by the building engineers, architects, and lighting designers was to carefully assess different interior and glazing designs for their effects on lighting requirements and lighting energy loads. They maximized the amount of daylight entering the building and then altered the interior design to maximize the dispersal of the natural light throughout the building. The designers used strategically placed windows and skylights on the exterior and an open office concept with low partitions heights in interior offices and partitions with glass upper portions on the exterior offices. These measures minimized the ambient lighting requirements of the building. The designers then focused on the use of energy-efficient task lighting for the remaining needs.

The building designers used the latest technology in lighting fixtures and design throughout the building. This included electronic-ballasted 30-watt T-8 lamp by Linear and Edison Price for the ambient lighting, and Herman Miller task fixtures in offices and other work areas. The NAS states that their energy savings in electricity for lighting are accomplished through the use of:[43]

- Task/ambient lighting system
  1. light is focused where it's needed, when it is needed
  2. all lighting fixtures and ballasts are highly energy-efficient
- Maximized use of daylight
  3. an open office plan incorporates strategic use of skylight and window lights
  4. glass topped interior walls allow natural light to reach interior spaces
- Occupancy sensors
  5. automatic switch lights on when space is occupied and off when space is empty
- Daylight dimming sensors
  6. automatically adjust the overall lighting based on the level of natural lighting
- Solar energy planning
  7. roof renovation has factored in computer-modeled solar analysis for energy application of solar energy. (This renovation involved the addition of a rooftop conference room, mechanical room and deck. It is also planned that solar collectors will be added at some point to generate some of the buildings energy requirements
- Results
  1. A typical US office uses 2.8 watts of power per square foot; Audubon uses well under one.

  2. Audubon saves approximately 80 cents on the dollar on electricity for lighting (compared with conventional office buildings)

  3. Using the Audubon approach, by the year 2000 we could save as much energy in the commercial sector as we currently consume.

2.7.5. Energy Conservation: Heating and Cooling

The NAS concern for the environmental impact of their new headquarters is clearly expressed in their desire to carefully reduce the energy consumed in heating and cooling the building by increasing the thermal resistivity of the building facade, glazing, and roof. The building designers were careful to avoid any insulating material that would outgas volatile organic chemicals (VOCs) and contribute to indoor air quality

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[43]National Audubon Society, *Audubon Headquarters: Building for an Environmental Future*

problems in a well insulated building. The designers used a light-weight concrete insulating product developed by Palmer Industries Inc. of Frederick, Maryland called Air-Krete™. The product is manufactured without the use of CFCs with a mixture of magnesium silicate and whipped sea water. The walls and roof are insulated to three times the national average which significantly reduced the heating and cooling energy requirements of the building and the size of the heating and air conditioning unit.

The use of large amounts of glazing for necessary adequate interior lighting presented the designers with the problem of high thermal gain and losses through the glazing. To combat this problem, the designers used *Skyline* double glazed windows with Heat-mirror™ inserts manufactured by *Southwall* technologies of Palo Alto, California. The windows are composed of two layers of one-quarter inch thick glass with a 2mm-thick layer of coated rigid polyester film. According to the NAS the use of energy for heating and cooling was reduced with:[44]

- A superior insulation system, or "thermal shell"
  1. by insulating three times better than the applicable energy code, the building retains heat in winter and keeps it out in summer
- Double-paned windows with "heat mirror" sheets
  2. allow light (but little heat) to penetrate in summer, retain heat in winter
- Highly efficient gas-powered heating and cooling unit
  the superior thermal shell and reduced lighting load enables use of down-sized gas-powered heating and cooling unit that takes a quantum leap in energy efficiency
- Result
  Audubon saves $40,000 annually on energy costs for heating and cooling.

[44]Ibid., p. 6.

2.7.6. Reducing Air Pollution

A major focus of the NAS was to reduce the amount of air pollution that resulted from the operation and maintenance of the building. The major reduction in air pollution came from source control measures directed at lowering the energy consumption of the building outlined in the previous section of this chapter. The NAS also directed their air pollution reduction efforts towards the type of heating and cooling equipment in the building and the choice of which building materials they would use. Their efforts included:[45]

- Use of environmentally sensible gas-powered heating and cooling unit which:
  1. reduces or eliminates harmful emissions harmful to most other systems
- Use of building and insulation materials free of ozone-depleting CFCs (chlorofluorocarbons)
- Electrical efficiency places less demand on coal and oil-burning power plants:

  2. power generation by these plants is one of the single largest sources of polluting gas emissions.

- Results:
  4. Audubon headquarters eliminates the two major sources of CFCs in new building construction: refrigerants in cooling systems (eliminated by using gas powered unit) and insulation.
  5. It drastically reduces acid rain due to the elimination of emissions of sulfur and nitric oxides
  6. By utilizing a gas-powered (instead of electric) heating and cooling unit, Audubon headquarters emits 62% less carbon dioxide and carbon monoxide, the principal gasses behind the greenhouse effect and global warming.

2.7.7. Indoor Air Pollution

Indoor air pollution and sick-building syndrome are possibly two of the least understood and controversial health problems in the US. The NAS approach to fighting the problem was consistent with their approach to minimizing other pollutants associated with the building. They practiced

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[45]Ibid., p. 6.

source control by eliminating any products in the building that might emit VOCs and they upgraded the HVAC system equipment and specifications. The steps they took included:[46]

- Improved air circulation system and higher fresh air ratio
  1. circulation system provides six air changes per hour, double the highest recommended standard.
  2. system draws in higher ratio of outside fresh air.
  3. system's high speed air-flow prevents the buildup of toxic bacteria and fungi, and avoids related health problems.
  4. building windows open to infuse fresh air at will.
- Use of non-toxic building and office materials
  5. commonly used materials release chemicals and solvents (e.g., formaldehyde and benzene) which can cause respiratory ailments, allergy problems, liver damage, and suppression of the immune system
  6. non-toxic materials used range from paints and wall coverings, to carpets and padding, to furniture and fabrics.
- Results
  7. Audubon has excellent indoor air quality and a healthy office habitat.
  8. The Society (NAS) and its people will benefit from a likely decrease in sick days and an increase in productivity. (fewer sick days will be simple to measure, measuring increases in productivity will be more difficult except using subjective indications)

2.7.8. Recycling

The other major concern of the NAS was that their new headquarters facilitate the implementation of a new modernization/operational program for the organization which includes recycling. This involved a five step approach which included: (1) recycling the building; (2) recycling demolition material; (3) using recycled post-consumer building materials; (4) installing an internal recycling system; and (5) establishing purchasing guidelines.

The NAS accomplished these objectives during the construction and design process. They purchased an old building and then made a determined effort to recycle as much of the building debris as possible during construction. They were able to recycle demolished concrete, glass, wallboard, bathroom partitions, masonry, and carpet. They tried to use building products

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[46]Ibid., p. 6.

with recycled content during construction including: steel, aluminum, gypsum wallboard, and ceramic tile. The NAS has established purchasing guidelines for all new products entering the building to assure some recycled content and to make sure the products are recyclable. The NAS also installed four disposal chutes for recyclables that lead to a basement recycling center. The trash is separated into high-quality paper, aluminum/plastics, mixed paper, and food waste. Bottles and other heavy recyclables are not dropped down the chutes for safety reasons. The NAS eventually intends to compost the food wastes on site. The NAS hopes to recycle 80% of the of the building's waste including nearly 42 tons of paper annually.

2.7.9. Case Study Summary

The NAS expects the results of their approach to building to be reflected in substantially lower life-cycle costs for the organization and society at large. The NAS building cost approximately $142 per square foot for demolition, site work, and construction. They estimated that the cost premium to be $172,000 on the building after a utility rebate of $110,715 was subtracted from the cost of energy-saving systems. This cost premium is expected to have a simple payback period of less than five years with additional savings stretching over the life of the building. For many people in the building and construction industry, these are the most significant aspects of the NAS building.

For others, it is the lesson that environmental considerations can drive the building process so that healthier, more profitable, and more environmentally sensitive buildings are built. The NAS took an environmentalist's life-cycle approach to building their new headquarters that had not been attempted on this scale in the US before. They proved the point that many in the building and environmental profession have been arguing for years, which is that there is a significant potential for cost-effective energy savings in the US building stock. If these energy savings measures are done correctly, there are significant financial benefits for the property owners and for the competitiveness of the US economy as financial resources are redirected to other uses.

2.8. Case Study: West Bend Mutual Insurance Company's New Corporate Headquarters

2.8.1. Introduction

The West Bend Mutual Insurance Company (WBMIC) has 400 full-time employees in its West Bend, Wisconsin corporate office building. The company had occupied an office building in downtown West Bend that was steadily expanded as the company grew. At the time the decision was made to construct a new office building, the company occupied 61,800 square feet. The construction of the old building represented typical modern commercial construction technology for the 1960 through 1980 period.

The primary motivation for building a new office building was that the company had outgrown their old building and further expansion was considered impractical. The other considerations for a new building were that the company could cost-effectively install the latest in office automation technology and systems for increased employee comfort and productivity. WBMIC officials determined that a new building, designed correctly, could significantly improve the competitiveness and productivity of the company.

The WBMIC used life-cycle-costing techniques in making decisions about alternative investments in their building. However, the scope of their analyses was much narrower than that of the National Audubon Society. The design professionals involved with the WBMIC building focused on aspects of the building that lowered the direct costs that the company would have to pay and that would increase employee productivity over the life of the building.

The building designers and WBMIC facilities managers used LCC analyses to focus on the heating and cooling costs, energy consumption, and maintenance costs of different alternatives. They did not take the cradle-to-grave approach advocated by the AIA Resource Guide or the NAS in analyzing building materials and equipment for the building. Nonetheless, the result is a building that has much less of an environmental impact than a conventional building. The building is possibly more representative of the type of approach to life-cycle-costing methods that will be used during the design process in the coming decades in the US than the approach used by the NAS and the Croxton Collaborative.

2.8.2. The Type of Work Being Done at WBMIC

It is important to understand the type of work that is done by most WBMIC employees to understand the motivation behind some of the decisions made during the construction process. The company is a property/casualty insurer that provides nearly forty different types of casualty and property insurance to commercial and personal customers. Most of the employees work in the underwriting and accounting departments processing different types of standardized forms and payment checks. Since a great deal of the work is very repetitive with standardized guidelines, the company is able to monitor the productivity of their employees using a computerized internal auditing program. The monitoring program actually measures the number of forms completed by each employee on a weekly basis. The results of the monitoring are used for promotion and salary reviews and are generally well accepted by the employees as a fair way of measuring performance.

The standardization of the work at WBMIC is important to the building process for several reasons. First it is virtually impossible for managers to ignore factors in the work environment which affect productivity because the results are so easily measured that they cannot be masked or avoided. Secondly, if new systems are installed to increase productivity, it is easier to monitor the results at WBMIC than it would be in other office environments where work types and loads vary significantly. The result is that WBMIC managers were very interested in employing the latest technologies and designs to increase worker comfort and productivity as a means of lowering the LCCs of the organization.

2.8.3. The Site

The WBMIC chose a 160 acre rural site for the location of their new building. The site was an abandoned cornfield that was virtually barren due to years of pesticide and fertilizer overuse. The WBMIC management made a decision to restore 60 acres of the cornfield with prairie grasses and wild flowers with good reason. The effort has had a positive environmental effect that has received very good publicity in the community. The site has become an amenity to the company and the local community where many of the employees live. Also, by looking at the LCC of this investment, the company realized that restoring the farmland was an inexpensive way to landscape and maintain their site.

Another important decision the company made regarding the site was to invest in two, two-level parking garages instead of large parking lots. The company worked with the site engineers to design the garages to be as unobtrusive as possible by hiding them behind earthen berms. The result is a much improved site where large parking lots are hidden from view.

2.8.4. The Building Structure and Facade

During the design and planning stage the WBMIC established policies to insure that the new building would fit the rural landscape as much as possible. They also established guidelines for purchasing local building products and using local tradesmen as much as possible.

The new building's four-story structure is made from locally-quarried limestone on the lower level with similarly pigmented local brick for the upper levels. Window and door trims are made from precast concrete sections which are significantly lower in cost. The glazing used on the structure is double-glazed and tinted with low emissivity coatings which are manufactured by Kawneer. The insulation system in the building is a conventional fiber glass and air pocket design but it is insulated to significantly higher levels than called for under local building codes.

WBMIC chose their mechanical contractors through a bidding process that included a design contest for the optimum HVAC design based on first costs, annual operating costs, and payback periods for enhancements. The final system included a partial ice storage system with standard electric air conditioning equipment backup for cooling and an electric furnace for heating. This system was chosen over alternative energy-efficient systems because the WBMIC officials liked its simplicity and that it was a proven technology. The company received a large utility rebate for the chill storage and other energy management devices as well as savings from off-peak energy use for cooling. The company utilized state-of-the-art equipment for their air distribution system including: vane-axial reheat fans, heat-tracing hot water pipes, and a full economizer cycle for the chillers for computer support areas.

WBMIC designers incorporated a raised floor throughout the new building to ease the wiring and rewiring of their extensive computer network. This raised floor also serves as the plenum for distributing air to the workstations throughout the building. Since the raised floor was required for the computer system, using it for air distribution significantly lowered the cost for the entire air distribution system. It also lowered the required ceiling height since the mechanical equipment could be underneath the floor not above the ceiling. This is one of the cost-effective tradeoffs that are possible when designers take an integrated approach to the building process.

The entire HVAC system is monitored by an energy management system developed by Johnson Controls sold under the product name Metasys™. This system incorporates environmental management, energy management, lighting control, and security and facility monitoring into one system. The system has centralized and discrete monitoring workstations that are distributed throughout the building. It is considered to be one of the latest in state-of-the-art facility-management systems.

2.8.5. Personal Environments Modules

One of the latest considerations in building design is the use of environmentally responsive workstations (ERWs) (see appendix 2.9.). ERWs allow individuals personal control over the lighting, temperature, air flow, and sound characteristics of their immediate environment. The WBMIC building contains the largest installation of ERWs in the US. The WBMIC units are called Personal Environments™ modules (PEMs) which are manufactured by Johnson Controls of Milwaukee, Wisconsin. The WBMIC site is being used as a test site for studying the affect of these innovative workstations on employee productivity.

The PEM™ manufactured by Johnson controls go further towards addressing the concerns of building professionals and employees than other similar products. These concerns include:[47]

1. Innovative HVAC system designs;
2. maximized individual control of environmental systems;
3. increased environmental contact for the individual;
4. effective pollution source control;
5. demonstration of concern for the environment and building resource management;
6. demonstration of concern for the effectiveness of the building systems; and
6. demonstration of concern for the health, comfort and satisfaction of the occupants.

WBMIC chose the PEMs™ manufactured by Johnson controls because they offered their employees control over the lighting, temperature, air flow, and sound characteristics of their work space. But additionally, each PEM™ can be adjusted for greater levels of outdoor air (OA) flow. WBMIC felt that the additional cost of the PEMs™ would be quickly paid for through the increased comfort and productivity of their employees.

Following the decision to install the PEMs™ in the new building, WBMIC and Johnson Controls commissioned a study by the Center for Architectural Research, and the Center for Services Research and Education at Rensselaer Polytechnic Institute. The study was intended to answer whether the PEMs™ did in fact have an affect on productivity and how much of an effect. The somewhat unique work situation at WBMIC made a study of this type possible.

2.8.6. Rensselaer's West Bend Mutual Study: Using Advanced Office Technology to Increase Productivity

The study began on January 2, 1991 with the study team collecting performance data on company employees at their old company headquarters for 27 weeks. The study team then collected similar data for 24 weeks at the

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[47]Vivian Loftness, et al., *Defining "fresh Air" Architecture: International Approaches to Healthier Buildings* p. 91.

new headquarters. The study was one of the most comprehensive of its kind because:

> "It used an established productivity monitoring system; combined objective productivity data with multiple subjective assessments of worker satisfaction and comfort; included measurements of three distinct influences on productivity (a major organizational relocation, a new built environment, and a new environmental conditioning technology); and included randomized experimental intervention to assure the internal validity of assessments of causal effects."[48]

The major objective of the study was to analyze the effects of the PEM™ "on office worker productivity, absentee rates, and worker response to environmental quality."[49] Besides using the existing productivity monitoring system at the WBMIC, the study team also used the Tenant Questionnaire Survey Assessment Method (TQSAM) developed for Publics Works of Canada (PWC). This system is used for measuring worker comfort and satisfaction levels in a building based on a standard questionnaire. The methodology for the study involved monitoring the number of files processed by each WBMIC employee in the old and new buildings during the study periods. During the study period in the new building, the air temperature, air velocity, and radiant heat panel of the PEMs™ were randomly disabled. The study group noted the following results:[50]

1. The combined effect of the new building and ERWs produced a statistically significant median increase in productivity of approximately 16% over productivity in the old building.
2. Partial disabling of ERWs (temperature, air velocity, radiant panel) resulted in a statistically significant 13% median decrease in productivity level compared to productivity in the new building after the move.
3. Data analysis examining the Mean Absolute Changes in Aggregate Productivity produced the following observations
   "Our best estimate is that ERW's were responsible for an increase in productivity of about 2.8% relative to productivity levels in the old building."

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[48]Walter Kroner, Jean Anne Stark-Martin, and Thomas Willemain, *Rensselaer's West Bend Mutual Study: Using Advanced Office Technology to Increase Productivity,* p. 3.

[49]Ibid., p. 3.
[50]Ibid., p. 4.

4. The disruption caused by the move from the old to the new building created a temporary productivity drop of approximately 30% using both analysis methods.
5. We found high week-to-week variability in individuals' productivity, as well as large variations across individuals. Because of this variability and the limits on the length of the study, the margins of error in our estimates were substantial. Despite these uncertainties about magnitudes of effects, the results are unambiguous regarding the existence and signs of the effects we measured.

It seems apparent from these statements, that the study team had some trouble accurately measuring the changes in productivity that can be directly attributed to the PEMs™. This is somewhat understandable given the difficulty of conducting a study like this where there are a large number of variables involved. In discussing the study with Bob Schmitt, WBMIC's facility manager, he stated the company felt the actual increase in productivity due to the PEMs™ was closer to 6%, but that the study used 2 3/4% because of the variability and limits of the study. He also stated the company was very happy with the increased productivity and that even an increase in productivity of 2 3/4% from the PEMs™ meant a payback period of less than one year. The company is also very happy with the maintenance aspects of the PEMs™ since the failure of a single unit does not affect the system as a whole. (see appendix 2.10.)

2.8.7. Case Study Summary

The motives for the WBMIC for building their new corporate office building using an environmentally sensitive approach are somewhat different than the motives of the National Audubon Society. The WBMIC was motivated by a desire to minimize the life-cycle costs of the building to the company in a cost-effective manner without increasing the initial costs of the building.

A more energy-efficient building facade was paid for with substantial savings from smaller lower-cost HVAC equipment. Other energy-saving items like lighting were justified by utility rebates and short payback periods. The PEMs could be justified from both their energy saving aspects and their effect on employee productivity. The ice storage system was justified by the company from a cost-savings standpoint and because of the utility rebate. The use of all these conventional technologies were integrated into a design that will save WBMIC millions of dollars over the life of the building.

Bob Schmitt stated that by utilizing this new approach to designing and constructing the building the company was able to build at a cost of $89 per square foot. These costs are equal to or less than the cost of conventionally built commercial buildings in the area which the company feels is one of the major reasons for promoting this type of design and construction. He stated that the building has an estimated value of $125 per square foot. This is partly a reflection of the additional amenities the company included to assure the highest possible comfort for their employees.

2.9. Chapter Conclusion

The construction market for energy-efficient buildings and for new systems that increase the energy efficiency of existing buildings is expected to be one of the growth markets in the construction industry. The increasing use of LCC methods for measuring the impact of design and construction decisions on the environment, energy consumption, and employee productivity is sure to have an impact. Even if LCC methods are used to measure the impact of design and construction decisions on the strategic objectives of the decision maker, the use of these methods will surely increase awareness of the broader implications of design decisions.

Chapter 3: Ground Source Heat Pumps

3.1. Introduction

Scientists, engineers, and manufacturers trying to introduce new technologies that reduce the United State's (US) demand for energy, face unique opportunities and challenges in establishing markets for their products. The recent introduction of one such product, the ground source heat pump (GSHP), is an excellent example of the potential of new energy-efficient products to significantly reduce America's energy consumption and emissions of airborne pollutants.

3.2. Technology Description

The technologies related to the design and manufacturing of heat pumps have been in widespread use since the early 1950s. Using the earth or groundwater for the heat sink for heat pumps, called ground source heat pumps (GSHPs), has also been practiced sporadically in North America for the past thirty years. Far more serious research and development (R&D) efforts devoted exclusively to GSHPs, have taken place in the last ten years as the technology has gained more widespread acceptance. With an increasing number of successful installations, it appears the technology may be at the early stages of a long period of rapid growth.[1]

GSHP systems use the heat contained in a water or a water/antifreeze solution that has been circulated through a series of closed-looped pipes buried in the ground which absorb some of the thermal energy stored in the earth. (see Exhibits 3.1. and 3.2.) In the heating mode, the system

[1]"Earth Energy Heat Pumps: Heating and Cooling from the Ground Up," (1989, AHP Systems, Inc,), p. 13.

Exhibit 3.1. Different Types of Ground Loop Systems

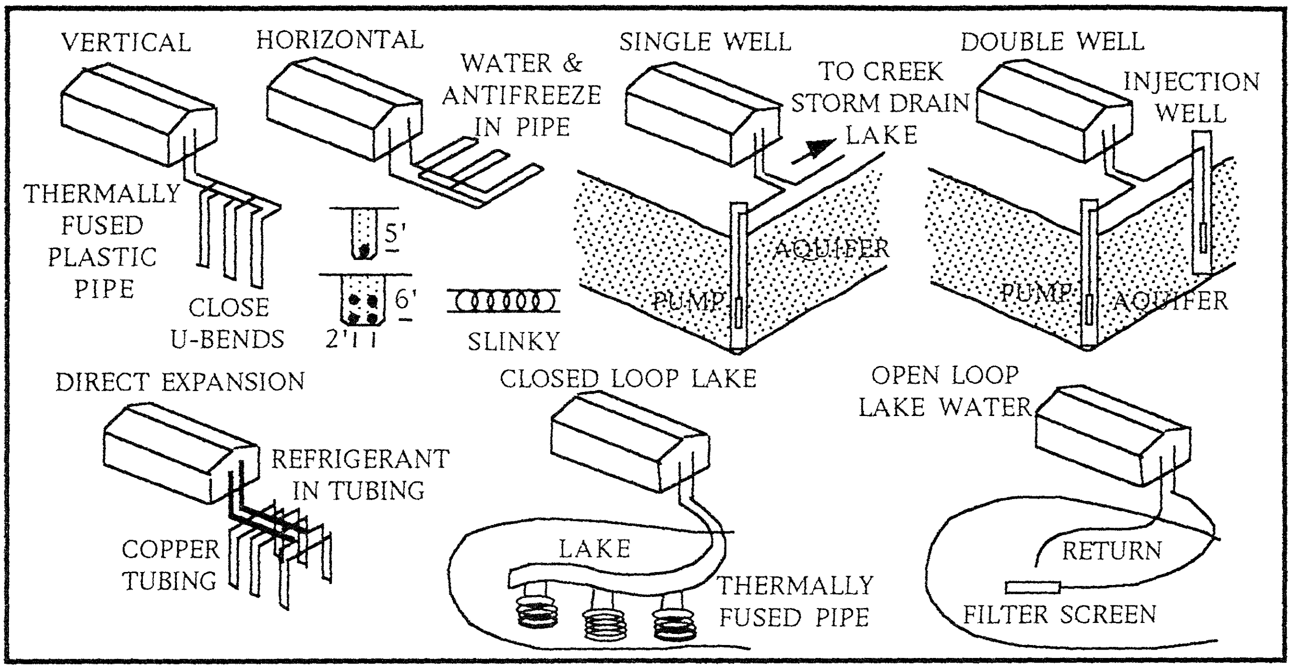
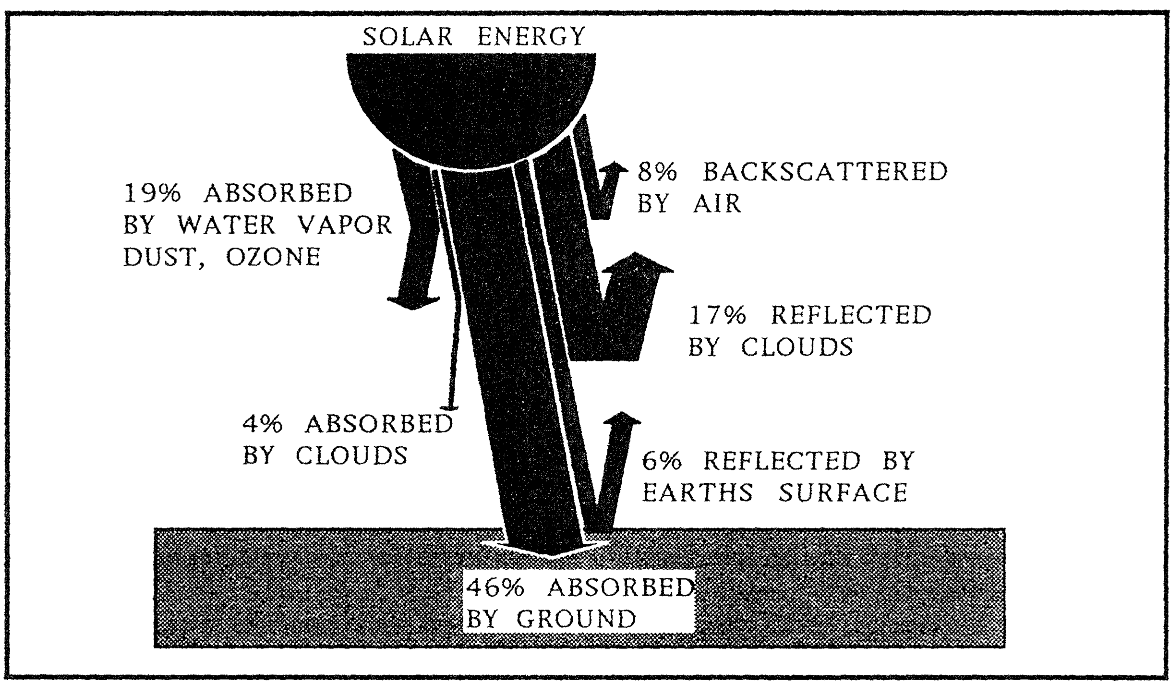


Exhibit 3.2. Solar Energy Absorption

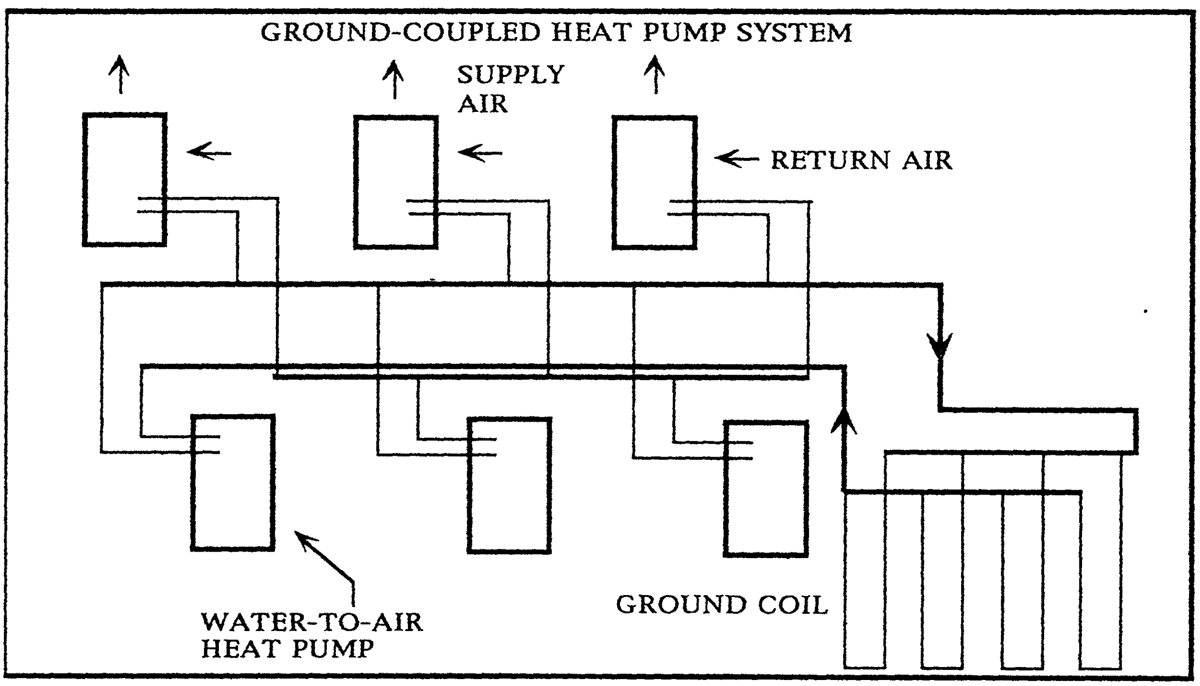


Source: EPRI Journal, September, 1991, p. 30.

collects heat from the earth, warms air in heat exchangers, and circulates the warm air through the building. To cool buildings, the system is reversed. Heat is removed by the heat exchangers, transferred to the cooling solution, and then into the ground. In this way the earth's thermal energy can be used as heat source or sink with substantial energy savings.

The conventional GSHP heating, ventilating, and air conditioning system is composed of three subsystems; the thermal source subsystem or ground-source heat exchanger (GSHE), the heat transfer subsystem or heat pump, a control system, and the thermal output subsystem consisting of ducts, fans or hydronic heat exchangers coupled with the remainder of the buildings HVAC system. (see Exhibit 3.3.)

Exhibit 3.3. Typical Commercial System



Source: "Ground Coupled Heat Pumps for Commercial Buildings," ASHRAE Journal, September, 1992.

For a residential building, the entire system is usually quite simple consisting of the GSHE, heat pump, a simple control system, and duct work. For a commercial application the system is far more complex. The ground-source heat exchanger might consist of hundreds of wells supplying different heat pumps for different zones in the building. Since these systems are often installed for energy-conservation reasons, they are usually monitored by sophisticated control systems to optimize their performance. A more thorough description of a large commercial application can be found in the case study of the Stockton State College application.

3.2.1. The Thermal Source Subsystem

The significant difference between conventional air source heat pumps (ASHPs) and GSHPs is the type of thermal source subsystem from which the heat is drawn. ASHPs use ambient outside air as the source or sink for heat while GSHPs use the mass of the earth or groundwater as the source or sink for heat.[2] The effectiveness of a heat pump is a function of the temperature difference between the thermal energy source and the thermal output. Earth or groundwater temperatures that are substantially higher than the loop temperature will greatly improve the efficiency of the system in the heating mode, and the opposite is true if the system is in the cooling mode. [3] The major drawback with ASHPs has been their inability to operate satisfactorily in cold weather. The warmed air being delivered from the thermal output subsystem into the living space in cold weather can be as low as 90°F and the residence may require an electric-resistance heat backup system which is costly to run and maintain. The ground and ground water however, remain at a more constant temperature which allows for an efficiency of operation for GSHP well above that for ASHPs even during periods of extremely cold weather. The biggest problem for the GSHP industry has been to develop a thermal source

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[2]"Ground Source and Hydronic Heat Pump Market Study," EPRI EM-6062, Project 2792-5, November 1988, p. 2-7.

[3]"Space Conditioning: The Next Frontier," (United States Environmental Protection Agency, April 1993), EPA 430-R-93-004

system that is simple and inexpensive enough to keep GSHPs competitive with more conventional heating and cooling systems. (see Exhibit 3.4.)

Exhibit 3.4. Vertical Versus Horizontal Loop Specifications

3-Ton System	Land Space Required	Trench/Hole Dimensions	Loop Length in feet	Loop Cost
HORIZONTAL	Up to 5,000 sq. ft.	Trench: 3-6 ft. deep 4-24in. wide 200-500 ft. long	1,200-1,800	$1,050-$1,500
VERTICAL	Up to 500 Sq. ft.	Bore Hole: 60-200 ft. deep 3-6 in. diameter	750-1,350	$2,100-$3,000

Source: "Space Conditioning: The Next Frontier," (United States Environmental Protection Agency, April 1993), EPA 430-R-93-004 p. 2-13.

A considerable amount of R&D effort has taken place recently focused on trying to optimize the ground-loop portion of the GSHP system. The efforts have been directed at developing heat transfer data for different soil types through studies funded by EPRI;[4] developing materials and techniques for fail-safe ground loops; and developing new installation techniques for lowering the cost and increasing the efficiency of the ground loops.

The studies, combined with more experience in installing GSHPs, has resulted in a number of different standard designs for the GSHE that can generally be classified as "open" or "closed" systems. The "closed" system or ground-loop system, consists of loops of polybutylene pipe where the pipe is buried in "horizontal loops" of various configurations depending on the building site, or in "vertical loops" in drilled wells. In these applications the pipe is filled with water or a water/antifreeze mixture which is circulated through the loop at a predetermined rate.

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[4]"Soil and Rock Classification According to Thermal Conductivity," EPRI CU-6482, Project 2892-3, August, 1989
"Soil and Rock Classification for the Design of Ground-Coupled Heat Pump Systems, Field Manual, EPRI, CU-6600, November, 1989

The horizontal loops take advantage of the considerable amount of solar energy that is stored in the ground close to the surface. Vertical loops take advantage of the geothermal energy that is in the ground and groundwater at lower depths. The wells for the vertical loops are usually grouted with a bentonite grout which enhances the heat transfer between the pipe and the ground but there are some advocates of leaving the well ungrouted and extracting the heat from the well water.[5] In the US, even with the lower cost of horizontal configurations, 54% of the installations have been vertical, 43% horizontal, and 3% are pond installations.[6]

One of the biggest drawbacks of the "loop" configuration is accidental or premature failure of the ground loop resulting in release of the water/antifreeze mixture into the water table. "Sixty five percent of the installations use propylene glycol or methanol. Some use sodium chloride, ethanol or no antifreeze at all."[7] Several of these antifreezes are considered toxic by the EPA, but the serious concern in the industry has resulted in several non-toxic alternatives. Chevron GS4™, a new anti-freeze developed specifically for GSHPs, is claimed by the manufacturer to be less toxic than table salt, non-flammable, readily biodegradable, and efficient.[8] However, the concern still lingers with consumers, and in the largest application of GSHPs in the US at Stockton State College in New Jersey, the closed-loop system will contain only stabilized water.[9]

EPRI recently sponsored R&D on the use of direct expansion closed-loop systems (DXGC) where the refrigerant is expanded directly into the ground

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[5]Conversation with Carl Orio, President, Water and Energy Corporation, Atkinson, NH.
[6]"Space Conditioning: The Next Frontier," (United States Environmental Protection Agency, April 1993), EPA 430-R-93-004 p. 2-16.
[7]"Space Conditioning: The Next Frontier," (United States Environmental Protection Agency, April 1993), EPA 430-R-93-004 p. 2-13.
[8]Ibid., p. 2-13
[9]"Stockton's Going Geothermal-Spring 1993 Update," Printed by Stockton State University, Pomona, New Jersey

loop. This increases the efficiency of the GSHP by eliminating the need for a fluid circulating pump and creating better heat transfer between the soil and the refrigerant. The major drawback with this system is the need for using copper piping in the ground loop which can corrode if highly oxidizing chemical substances are present in the soil.[10] Leaks in the ground loop would be impossible to fix without excavating the entire loop until the leak was found. The efficiency increases of the DXGC and the need for using much smaller ground loops has maintained the interest in doing R&D work in the US. Work in Europe has indicated potential payback periods of eleven years for systems used only for heating and in the US, where the system could be used for heating and cooling, the payback could be as little as six years.[11] However, the technical considerations in designing, installing and maintaining a system of pressurized-copper ground loops filled with refrigerant and a small amount of lubricating oil will probably prevent the widespread application of this technology in the US over a far more reliable system of plastic piping.

"Open" GSHE types depend on an adequate source of water from which water is drawn and then discharged back into. Ponds, lakes and rivers have been used for the source but there are several drawbacks to these systems which will prevent widespread application of this technology. Environmental regulations in many states require permits to withdraw and then discharge heated water into a water source or to do the reverse when using the GSHP for air conditioning. Minerals from the water source can contaminate the heat exchanger in the heat pump and lower its efficiency. Treating the large quantity of water required for this type of system to eliminate this problem is also impractical. Some older systems exist where water is drawn from wells and

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[10]"Design Guidelines for Direct Expansion Ground Coils," EPRI CU-6828 (Electric Power Research Institute, May 1990), p. 6.
[11]"Design Guidelines for Direct Expansion Ground Coils," EPRI CU-6828 (Electric Power Research Institute, May 1990), p. 5.

then discharged into lakes or streams. New permits for this type of open-loop system where water is drawn from one source and discharged into another are very difficult to acquire because of environmental considerations.

3.2.2. The Heat Transfer Subsystem: Heat Pumps

The heat pumps used in a typical GSHP system, are very similar in design to ASHPs . (see Appendix 3.1.) The thermodynamic process of the heat pump is:

> "In the heating mode, the cycle starts as cold refrigerant passes through a heat exchanger or evaporator and absorbs heat from the low temperature water supplied from the ground loop. The refrigerant evaporates into a gas as the heat is absorbed. The gaseous refrigerant then passes through a compressor where the refrigerant is pressurized, raising the temperature to over 180 degrees Fahrenheit. The hot gas then circulates through a refrigerant-to-air heat exchanger where the heat is removed and pumped into the buildings. When it loses its heat, the refrigerant changes back to a liquid. The liquid is cooled as it passes through an expansion valve and the process begins again. To become an air conditioner the process is reversed."[12] (see Appendix 3.1.)

The efficiency of heat pumps has significantly improved since their first introduction in the 1950s. Large-scale R&D efforts with funding from the Department of Energy (DOE), the Environmental Protection Agency (EPA), Electric Power Research Institute (EPRI) and numerous manufactures, have steadily advanced the state-of-the-art in heat pump design and manufacturing. Although most of the R&D until recently has been focused on improving the efficiency of air source heat pumps (ASHP), many of the design improvements in heat pump technology have also been incorporated into GSHPs. With increased support from the EPA for more widespread use of GSHPs because of their energy saving and environmental benefits, R&D efforts devoted solely to GSHPs should increase.

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[12]"Stockton's Going Geothermal-Spring 1993 Update," Printed by Stockton State University, Pomona, New Jersey

Recent collaborative efforts between EPRI and Carrier, the leading manufacturer of air conditioning equipment in the US, to develop more efficient air-source heat pumps have resulted in marked improvements in the design and engineering of new products. These new heat pumps are quieter and more energy efficient and they feature programmable controls, variable speed compressors, and integrated hot-water heaters.[13] Many of these developments have been incorporated into the latest GSHPs which has increased their competitiveness in the market for advanced heating and air conditioning equipment. Exhibit 3.6 shows s a comparison between ASHP and GSHP in several critical areas.

Exhibit 3.6. Ground Source Heat Pump and Air Source Heat Pump Design and Performance Comparison

3-Ton System	GROUNDSOURCE HEAT PUMP	AIR SOURCE HEAT PUMPS
Qty of R22 Refrigerant	3 lbs.	6-7lbs.
Location of Compressor	Inside House	Outside House
First Cost	$5,599-$8,8615	$3,200-$8,180
End Use Efficiency: Seasonal Performance Factor-Heating	2.74-5.37	1.56-2.93
End Use Efficiency: Seasonal Performance Factor-Cooling	2.82-5.99	2.30-4.33
Temp. of Air Entering house - heating season	90° - 100° F	80° - 100° F

Source: "Space Conditioning: The Next Frontier," (United States Environmental Protection Agency, April 1993), EPA 430-R-93-004 p. 2-13.

[13]"The Advanced Heat Pumps," (EPRI Journal, March, 1988), p. 5.

3.3. Technology Content

3.3.1. Effectiveness

The EPA has recently completed an in-depth study of advanced electric, gas, and oil space conditioning equipment for the residential market in the U.S.[14] The EPA study used a variety of different analytical methods in reaching their conclusions. (see Exhibit 3.7,) Six different locations in the U.S. were studied: (1) Burlington, Vermont; (2) Chicago: (3) the upper New York City metropolitan area; (4) Portland, Oregon; (5) Atlanta; and (6) Phoenix. Four different electric power generating fuel mixes were studied for their air emissions in each region: (1) a "regional generating mix" similar to the actual fuel mix in each region; (2) a natural gas combined cycle (NGCC) generating plant as the marginal unit; (3) an advanced fluidized bed coal (AFBC) plant as the marginal ; and (4) a natural gas combustion turbine (NGCT).[15] The emissions of CO_2, SO_2, and NO_x from each fuel mix were assigned dollar-per-kilogram values that were added to the base cost and operating cost of the different units.

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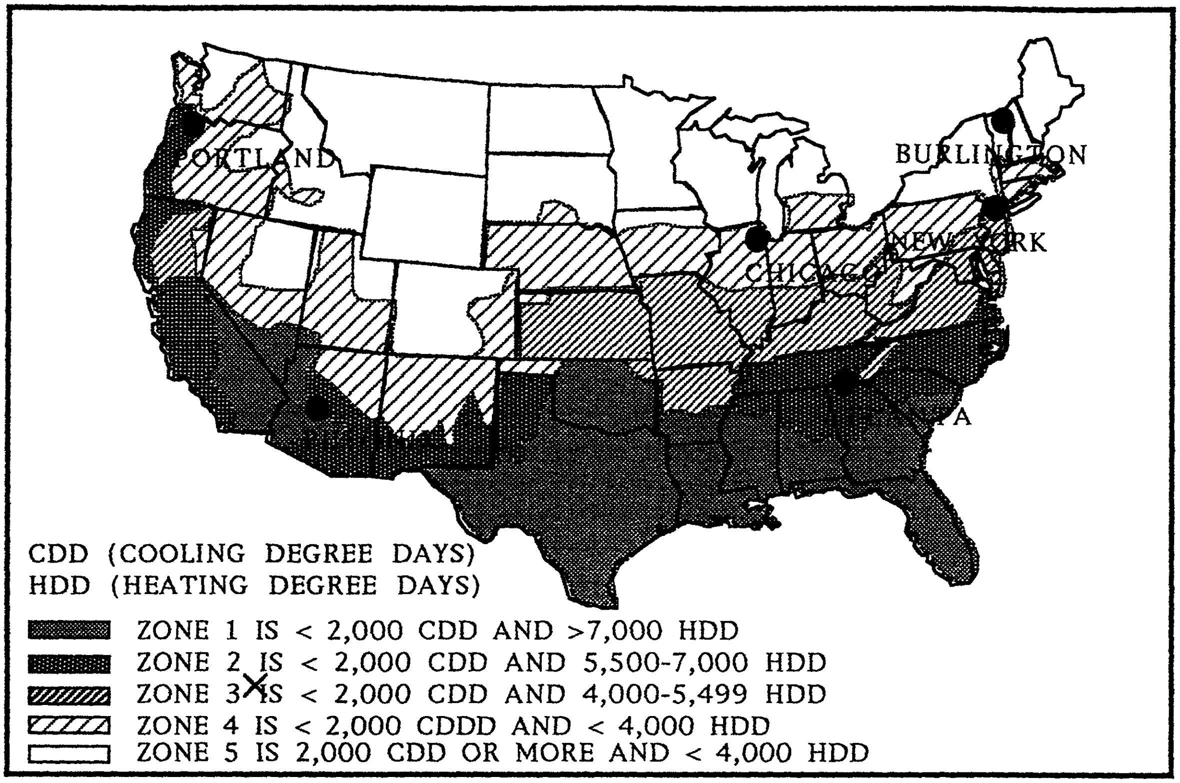
[14]"Space Conditioning: The Next Frontier," (United States Environmental Protection Agency, April 1993), EPA 430-R-93-004

[15]Ibid., p. ES-5.

Exhibit 3.7. Climate Zones for the Continental United States



Source: "Space Conditioning: the Next Frontier," EPA 430-R-93-004

The results of this study verify the effectiveness of the newest or emerging ground source heat pumps (EGSHPs). The EPA report states that energy consumption and emissions can be reduced by 23-44% over the most advanced ASHPs, and by 63-72% compared to electric resistance heat with standard air conditioning equipment. Under most regional fuel mix scenarios, except where coal-intensive electric power generating equipment is used, EGSHPs had the lowest overall environmental costs. For AFBC as the marginal unit, gas-fired heat pumps (GFHP) had the lowest CO_2 emissions but higher NO_x emissions than other technologies, especially AGSHPs. (see Exhibit 3.8.)

Exhibit 3.8. Space Conditioning Equipment Externalities

BURLINGTON Regional mix	CO2 (kg)	CO2 Saved Over Worst	NOx (kg)	SO2 (kg)	CO2 ($)	NOx ($)	SO2 ($)	Exter-nality Cost	Annual Operating Cost	Total Societal Cost
Emerging Ground Source Heat Pump (SLINKY)	2,579	7,517	6.5	26.1	$33.5	$41.8	$22.93	$98	$1,781	$1,879
Emerging Ground Source Heat Pump (VERTICAL)	2,579	7,517	6.5	26.1	$33.5	$41.8	$22.93	$98	$1,918	$2,016
Advanced Ground Source Heat Pump	3,137	6,959	7.9	31.7	$40.8	$50.9	$27.89	$120	$2,094	$2,214
Standard Ground Source Heat Pump	3,585	6,511	9.1	36.2	$46.6	$58.1	$31.87	$137	$2,194	$2,331
Advanced Air Source Heat Pump	4,574	5,522	11.6	46.2	$59.5	$74.2	$40.66	$174	$2,504	$2,678
Advanced Air Source Heat Pump (low Cost)	4,574	5,522	11.6	46.2	$59.5	$74.2	$40.66	$174	$2,302	$2,477
High-Efficiency Air Source Heat Pump	5,956	4,141	15.0	60.2	$77.4	$96.5	$52.94	$227	$2,607	$2,834
Standard Air Source Heat Pump	6,382	3,715	16.1	64.5	$83.0	$103.5	$56.72	$243	$2,661	$2,904
Electric Resistance	9,194	903	23.2	92.9	$119.5	$149.1	$81.72	$350	$3,497	$3,848
Gas-Fired Heat Pump	6,011	4,085	16.2	4.5	$78.1	$104.0	$3.93	$186	$1,752	$1,938
Advanced Gas Furnace	6,463	3,633	6.5	5.20	$84.0	$41.6	$4.58	$130	$1,812	$1,942
Standard Gas Furnace	8,138	1,959	8.1	6.3	$105.8	$52.1	$5.53	$163	$1,945	$2,108
Oil Furnace	10,096	0	10.0	32.9	$131.3	$64.3	$28.94	$224	$2,011	$2,236

Source: "Space Conditioning: the Next Frontier," EPA 430-R-93-004
April, 1993

In most areas of the country the total environmental cost of GSHP and advanced ASHP were the lowest for a NGCC scenario as well.[16] The EPA estimated that aggressive promotion of these new technologies by electric and gas utilities just in the residential space heating market, could reduce U.S. CO_2

[16]Ibid., p. ES-5.

emissions by 25 million metric tons, SO_2 emissions by 85,000 metric tons, and NO_x emissions by at least 44,000 metric tons by the year 2000.[17] EPA also estimates that 28 billion kilowatt-hours of electricity could be saved, negating the need for 113-330MW power plants.[18]

These new spaceheating technologies, especially GSHPs, are highly effective new technologies for reducing energy consumption and airborne emissions. GSHPs could significantly improve the supply-side of the energy production-consumption cycle by increasing energy efficiency, lowering peak-demand levels, improving the load factor of the supply system, and increasing the cost effectiveness of electric heating. On the demand-side, lower energy bills are somewhat offset by higher capital costs, but increasing proliferation of this technology will certainly lower the capital costs and economies of scale are realized.

3.3.2. Problems and Costs: The Ground Loop

The major problems limiting more widespread use of GSHPs is the high capital cost of installing the ground-loop portion of the system. Currently, the ground loop accounts for 36% of the installed cost of a GSHP system ranging between \$500 and \$1500 per ton of capacity.[19] (see Exhibit 3.9.) Trenching for horizontal loops or drilling for vertical loops, installing and testing the piping, plus additional pumps and controls, add significantly to the cost of GSHPs.

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[17] Ibid., p. RF-1.
[18] Ibid., p. RF-1
[19] "Geothermal Ground-Loop Preinstallation Project at Walden Pond," (Public Service Company of Indiana, Plainfield, Indiana), EPRI CU-6969 p. 1-1.

Exhibit 3.9. Annual Costs of Space Conditioning: Upper NY. Area

EQUIPMENT TYPE	Installed Cost	Annual Capital	Annual Operating	Total Cost
Emerging Ground Source Heat Pump (SLINKY)	$8,425	$829	$736	$1,566
Emerging Ground Source Heat Pump (vertical)	$9,410	$926	$736	$1,663
Advanced Ground Source Heat Pump	$9,410	$926	$881	$1,807
Standard Ground Source Heat Pump	$9,005	$886	$1,062	$1,948
Advanced Air Source Heat Pump (Present Cost)	$9,255	$911	$1,034	$1,945
Advanced Air Source Heat Pump (low Cost)	$7,470	$735	$1,034	$1,770
High Efficiency Air Source Heat Pump	$6,925	$682	$1,402	$2,084
Standard Air Source Heat Pump	$6,115	$602	$1,541	$2,143
Electric Resistance/Standard AC	$5,615	$553	$2,352	$2,905
Gas-Fired Heat Pump	$8,000	$787	$853	$1,640
Advanced Gas Furnace/High Efficiency AC	$7,200	$709	$932	$1,640
Standard Gas Furnace/Standard AC	$5,775	$568	$1,138	$1,706
Advanced Oil Furnace/High Efficiency AC	$6,515	$641	$1,162	$1,803

Source: "Space Conditioning: the Next Frontier," EPA 430-R-93-004
April, 1993

A considerable amount of research has been done on reducing the cost of the ground loop portion of the GSHP system. EPRI has calculated that a $1000 price difference between GSHPs and other advanced residential spaceheating equipment will require a 20% reduction in the cost of the ground loop and heat pump. EPRI has estimated this cost difference could be recovered in as little as five years through energy savings for the typical residential homeowner.

EPRI and several other organizations have sponsored research on reducing the cost of installing ground loops. EPRI published the results of a project as part of this effort entitled "Soil and Rock Classification According to Thermal Conductivity: Design of Ground-Coupled Heat Pump Systems." The intent of the study was to identify the major soil types in the U.S. and establish thermal conductivity and heat diffusivity ranges for them that could be used to design ground loops. Correct classification of the soil type allows the designers to minimize the length of the ground loop while assuring correct operation of the GSHP. (see Exhibit 3.10.) The cost savings can be substantial because the thermal conductivity and heat diffusivity ranges vary so widely for different soil types. For example, a horizontal-one pipe system in "heavy-damp" soil would need to be 353' per ton of heat pump capacity, but 729' per ton in "light dry" soil.

Exhibit 3.10. Soil Thermal Properties

Thermal Texture Class	Thermal Conductivity W/m°K	Btu/ft °F	Thermal Diffusivity cm^2/sec	ft^2/day
Sand (or gravel)	.77	0.44	.0045	.42
Silt	1.67	0.96	- -	- -
Clay	1.11	0.64	.0054	.50
Loam	.91	0.52	.0049	.46
Saturated Sand	2.50	1.44	.0093	.86
Saturated Silt or Clay	1.67	0.96	.0066	.61

Source: Soil and Rock Classification for the Design of Ground Coupled Heat Pump Systems, Field Manual, EPRI CU-6600, November, 1989.

Another study by EPRI and the Public Service Company of Indiana (PSI) focused on reducing the cost by preinstalling the ground loops in a large residential subdivision. The projects intent was not only to demonstrate that economies of scale are possible in installing the ground loops, but to "stimulate interest in GSHPs among homeowners, builders, developers, and electric utilities."[20] The project involved the preinstallation of 36 horizontal loops at an average cost of $1502, and 28 vertical loops at an average cost of $2860. EPRI and PSI estimated a cost reduction of 34% over installation of the loops one at a time.[21] The project did succeed in proving the effectiveness of preinstalling

[20]Ibid., Report Summary
[21]Ibid., Report Summary

the loops, but other unforeseen problems did occur, in part, because of the novelty of this approach. These included: last minute design changes requested by the homeowners; unexpected obstructions such as boulders; and changes in the house sizes and locations that were requested by the developer.

Other research efforts aimed at lowering the cost of the ground loop have included R&D and installation of direct coupled heat pumps (DXGC). With these heat pumps, the air-to-refrigerant heat exchanger can be removed and the refrigerant lines connected directly to the copper ground coils. The heat transfer between copper lines filled with refrigerant range from 100 to 160Btu/hr-ft for heating and 160 to 220 Btu/hr-ft for cooling. This is much higher than the 20Btu/hr-ft for heating and 50Btu/hr-ft for cooling for secondary fluid GSHP systems. This means that ground loops can be significantly shorter for DXGC systems and more efficient. However, environmental concerns over possible leaking of the copper lines, and system design and operating problems will probably limit the use of DXGC systems in the US.[22]

3.3.3. The Heat Pump

The heat pump portion of the GSHP represents nearly 36% of the installed cost of a residential GSHP. This figure is not unusually high for an energy-efficient product, and greater economies of scale are expected as the market develops. Unfortunately, low sales of GSHPs are partly the result of the high cost of purchasing the units, which limits any hope for achieving economies of scale that higher sales might bring. This is a common problem with the introduction of many new energy-efficient products.

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[22]"Design Guidelines for Direct Expansion Ground Coils," EPRI CU-6828 (Electric Power Research Institute, May 1990), p. S-1.

3.3.4. The Air Distribution System

The ductwork, controls, and labor associated with the installation of the air distribution system represent 20% of the installed cost of the GSHP. This is similar to the cost of installation for this part of any air conditioning or heating system and its cost does not represent a problem in selling the GSHP system.

3.3.5. Installation

Additional miscellaneous materials, labor, overhead, and profit represent 5% of the cost of installing a residential GSHP. This is similar to installation costs for other heating and cooling equipment and it does not represent a barrier to the widespread use of this technology.

3.3.6. Patent Status

A variety of patents cover the mechanical equipment in a typical GSHP system as might be expected. Several types of ground-loop designs are also patented. Proprietary trenching equipment has also been developed that is patented and different GSHP programs developed by utilities have licensed trademarks. The International Ground Source Heat Pump Association (IGSHPA) is also working to have GSHP contractors, designers, and manufactures licensed and to establish standards for the industry. This will help to maintain the integrity of the industry and to prevent substandard installations that might damage the reputation of the technology.

3.3.7. Research Groups, Companies, Organizations Developing Technologies

Various groups, organizations, and individuals are actively researching, developing, and promoting GSHP technologies. These include:

The Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA, 94304

Public Service Company of Indiana
1000 East Main Street
Plainfield, Indiana 46168

The U.S. Env. Protection Agency
Office of Air and Radiation
Washington, DC, 20460

Oak Ridge National Laboratory
Energy Division
Oak Ridge, TN, 37831

International Ground Source Heat
Pump Association
101 Industrial Building
Stillwater, OK, 74078-0532

3.4. Regulatory and Social Acceptability

3.4.1. Legal/Regulatory Acceptability

3.4.1.1. Mandatory Technologies

The technologies associated with the use of GSHPs are not mandatory. The studies conducted by various government agencies on the technology are generally quite favorable, particularly the recent study by the EPA "Space Conditioning: The Next Frontier." However, none of these agencies have called for mandating the use of GSHPs through direct regulations or any type of market mechanism.

3.4.1.2. Permitting

For residential applications the permitting process is quite simple and requires little more than a residential building permit. Larger commercial applications may require the filing of environmental impact statements to assure that using the ground as a heat sink or source does not cause over-heating or cooling of the groundwater. Unlimited heat extraction from the ground has caused some concern in Europe where commercial applications of GSHPs are more widespread.

There is also a real fear within the GSHP industry that widespread applications of the technology by inexperienced contractors might lead to accidents involving leakage of the water/antifreeze mixture in the ground loop into the ground water. Any increase in accidents as the technology penetrates the market might necessitate government regulation of the entire industry.[23] This concern has led to the development of "environmentally friendly" antifreezes, attempts at self-regulating by the industry, and the use of distilled water in the ground loop which then must be buried below the frost line. For now the GSHP industry is considered relatively regulation free and it enjoys the support of most government regulatory agencies.

This is not the case for open loop GSHP systems, particularly systems where ground water is extracted from wells and pumped into nearby water bodies. There is considerable opposition to these systems within the regulatory agencies where they are considered environmentally unsound; consequently it is difficult to acquire the necessary permits to install them.[24]

3.4.2. Associated Liability

The major liability issue with GSHP that is unique to this product is an accidental leak of the water/antifreeze mixture into the groundwater. With the recent introduction of factory-welded high density polyethylene or polybutylene pipe this is not considered a major concern. The best piping products carry a fifty year warranty if installed correctly.[25] Several manufacturers have also developed new antifreezes that they claim are even more environmentally friendly than the popular propylene glycol and methyl alcohol antifreezes that are more commonly used. GSHP contractors have also used plain water in the ground loops which would eliminate any concern regarding liability for ground water contamination from leaking.

The likelihood that GSHP contractors might be held liable for excessive withdrawal of heat from the ground is fairly remote. Studies indicate that the

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[23]Conversation with Carl Orio, President, Water and Energy Corporation, Atkinson, NH.
[24]Ibid.,
[25]"Earth Energy Heat Pumps: Heating and Cooling from the Ground Up," (1989, AHP Systems, Inc,), p. 9.

ground water temperature recovers fairly quickly and that temperature changes are quite localized. [26] This situation might change somewhat if the technology is used more widely for large commercial projects in more densely populated areas.

The liability associated with open-loop GSHPs for the contractor needs to be assessed on a case by case basis. Certainly, any excessive removal of groundwater or haphazard discharging is going to face serious opposition from public and regulatory organizations that might seek legal action to stop the activity. It is unlikely that a system like this would be acceptable to potential customers.

3.4.3. Public Acceptability

In a customer opinion poll of GSHP system owners conducted by the Public Service Company of Indiana (PSI), 97% indicated "that they were satisfied with their purchase and would buy again."[27] The customers also ranked GSHP "higher in comfort, economy, and reliability than any other technology."[28] These findings indicate very favorable acceptance of the technology within the established customer base of the GSHP market.

More generally, a lack of public awareness of the product has meant that there is not a widespread or established public opinion of GSHP that has had any real effect on the market. Recent public awareness efforts and several large commercial projects have changed this situation some and there is evidence to suggest that what public opinion there is, is very favorable.

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[26]"Design Guidelines for Direct Expansion Ground Coils," EPRI CU-6828 (Electric Power Research Institute, May 1990), p. 5.

[27]"Geothermal Energy: Clean, Sustainable Energy for the Benefit of Mankind and the Environment," (Earth Science Laboratory, University of Utah Research Institute, October, 1991)

[28]"Geothermal Ground-Loop Preinstallation Project at Walden Pond," (Public Service Company of Indiana, Plainfield, Indiana), EPRI CU-6969 p. 2-1.

3.4.4. Political Acceptability

The literature on GSHPs indicates a very favorable, although not very widespread, opinion of this technology among political and government organizations. The technology suffers more from political ignorance than from any low opinion of the product. The recent endorsement of GSHPs by the EPA and the DOE for the technology's potential to save energy and lower airborne pollution emissions, may create more widespread political support for the technology. Promotion of GSHPs by the utilities and through EPRI should also help in gaining more political recognition and acceptability of the technology at all levels of government. Large commercial applications such as the systems at the Oklahoma Capital Building and Stockton State College should also help in gaining political acceptability for this technology.

3.4.5. Related Public Health and Environmental Issues

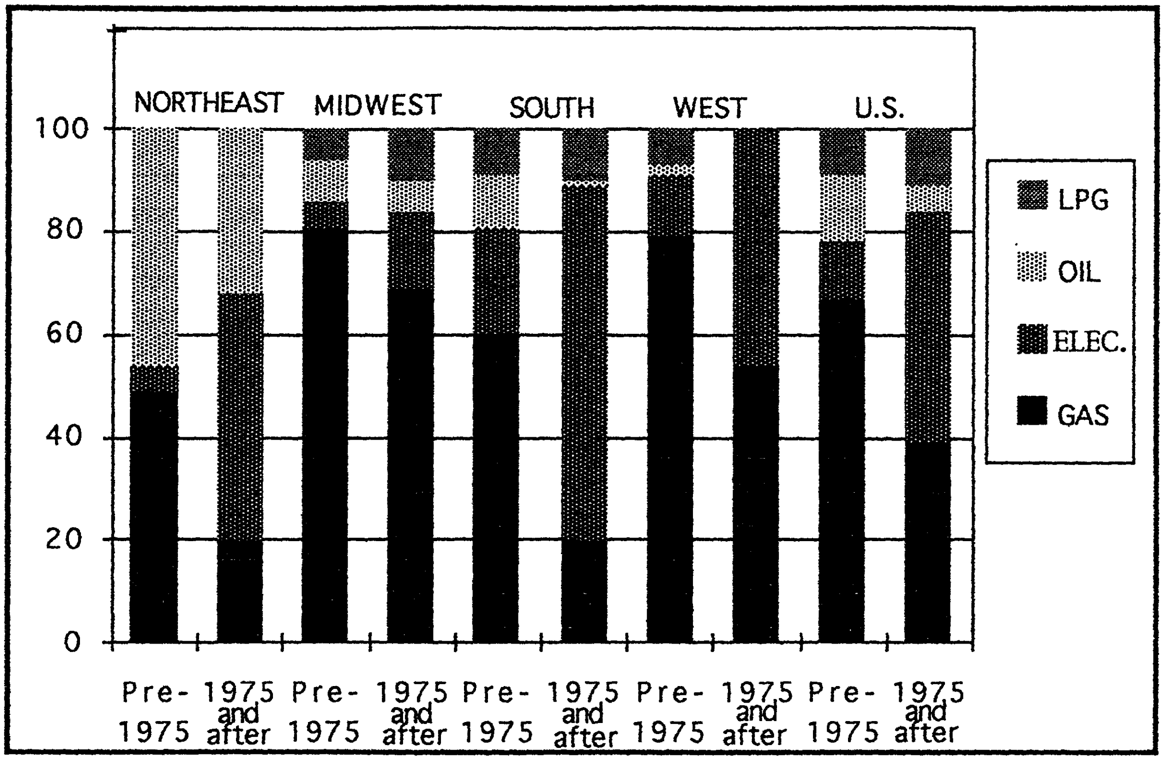
As discussed previously in this report, the major public health and environmental concerns with GSHP are the potential for groundwater contamination through leaks in the ground loop. The other concern is excessive heat extraction from the ground in densely populated areas for commercial applications. Neither of these issues are a major concern at this time.

Another environmental concern is the ozone-depleting refrigerants in the heat pumps. Although GSHPs use 25% less refrigerant than ASHPs, any amount is still a concern. Manufactures of GSHP and ASHP are addressing this issue by sealing the heat pumps at the factory and redesigning the products to use the most environmentally benign refrigerants.

3.5. Market Characteristics

3.5.1. Market Size: Present

Exhibit 3.11. Major Heating Fuel Used for Homes Built Before 1975 VS. Homes Built 1975 or Later



Source: "Space Conditioning: the Next Frontier," EPA 430-R-93-004, April, 1993

In 1991, approximately 838,000 single family homes were built in the U.S. Of these, 65% had warm air furnaces, 23% had electric heat pumps, and 12% had some other type of spaceheating system. 32% of the homes installed equipment that uses electricity as the energy source, 60% gas, 4% oil, and 4% some other type of fuel. The use of these sources of fuel has changed significantly in the past 20 years as Exhibit 3.11 shows. The general trend since 1975 has been a steady increase in the use of electricity instead of natural gas or oil. The percentage of new homes installing central air conditioning has also increased dramatically in the past ten years. This means that utilities will face higher demand during peak-summer periods if more demand-side management is not practiced including the installation of more efficient air conditioning systems.[29]

The markets for space conditioning equipment are large and fairly stable although lower new construction activity has dampened demand somewhat. In 1990, 2 million gas furnaces were sold, of these 1.4 million were for the retrofit market. Estimates for sales of gas furnaces in 1995 range between 2.0 and 2.4 million units.[30] In 1989, the total sales for heat pumps reached 660,000 units of which 313,000 were for retrofits. In 1991, total sales were close to 715,000 units with 374,000 units installed as retrofits. These figures show good sales growth for ASHPs despite a dramatic decline in new construction in the Southern U.S. which has traditionally been the best market.[31] The rise in the number of retrofits is an indication that an increasing percentage of the older units are being replaced and EPRI has projected that this trend will continue. EPRI has estimated that total heat pump production will reach 1.4 million units by the year 2000 and 1.4 to 1.6 million by the year 2005.[32] EPRI has also done research that indicates 100% of the heat pumps being retired are replaced with new heat pumps.[33]

The market for air conditioning equipment in the U.S. is also quite large. Total shipments for central air conditioners was 2.92 million units in 1990 up from 2.5 million units in 1989. In 1989, 2 million of the units sold were for retrofits and 0.5million were for new construction.[34]

The current market for GSHPs is significantly smaller than the market for natural gas, ASHPs, or central air conditioners which they could replace.

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[29]"Space Conditioning: The Next Frontier," (United States Environmental Protection Agency, April 1993), EPA 430-R-93-004 p. 2-3.
[30]Ibid., p. 2-3.
[31]Ibid., p. 2-3.
[32]Ibid., p. 2-6.
[33]Ibid., p. 2-6.
[34]Ibid., p. 2-6.

Sales figures are difficult to find because the manufacturers do not publish any. 1992 estimates done by trade journals indicated sales of about 20,000 units for residential heating. The number of sales has remained steady at this size since 1985, but this is in spite of a significant slowdown in the residential construction market.

Commercial installations of GSHP are fairly limited at the current time. Actual figures for commercial applications are even more difficult to find than those for residential applications, but the number is certainly quite low given the potential size of the market. The trade journals indicate that most of these applications are in light-commercial buildings, restaurants, schools, etc., where high energy demands mean a quicker return on the higher capital investment. One Pennsylvania based firm, HEATEC, specializes in installing and operating GSHP systems in commercial buildings. (see Exhibit 3.12.)

Exhibit 3.12. HEATEC Installations

Building Type	Area (ft^2)	Capacity (tons)	Heat Pumps	Number of Bores
Bank	5,500	13	3	3
Retirement Community	420,000	840	316	187
Elementary School	24,000	59	21	20
Doctor's Office	11,800	35	7	7
Condominiums	88,000	194	74	40
Middle School	110,000	412	96	106
Restaurant	6,500	36	6	7
Office/lab	104,000	252	43	62
Elderly Apartments	25,000	89	76	12
Life Care Community	390,000	1,100	527	263

Source: ASHRAE Journal, September, 1992. p. 32.

3.5.2. Market Size: Future

There is little doubt that GSHPs have a real potential to penetrate the residential and commercial space heating and cooling market in the U.S. The technology has a proven track record of tens of thousands of installations where the system's efficiency and low maintenance has significantly lowered costs for consumers. Unfortunately, two major market barriers have prevented more widespread market penetration of GSHPs.

The biggest market barrier for GSHP is the higher capital cost of the product. Consumers are willing to pay the price premium only if high rates-of-returns give payback periods between two and three years. The second barrier is the tenant-landlord relationship in which one third of U.S. households are involved. Unfortunately in a rental situation, neither party has any real incentive to take energy savings measures. Landlords rarely pay the utility bills and tenants realize they will probably move before any savings would be incurred from energy saving improvements.[35] These two market barriers are not only a problem for GSHP manufacturers, but for many manufactures of energy efficient products that are more costly.

To overcome these market barriers to increased energy efficiency, many electric utilities have developed demand-side management programs as part of larger integrated resource management (IRM) plans. IRM is a method for analyzing the total cost of supply-side and demand-side resources so that utilities can supply electric power at the least cost to society. Estimates of demand-side spending by utilities suggest that spending might reach $50 billion by the year 2005[36]. This spending represents a significant amount of money being spent on energy-efficient products. How it is spent will have a real impact on the future growth of the GSHP market. The potential is there for the utilities to overcome the market barriers that GSHPs and other energy related products face through direct subsidies to consumers and manufactures.

The USEPA, using estimates developed by an electric utility, has projected the market potential for advanced space heating and cooling systems for a "typical" single-family home with air conditioning. (see Exhibit 3.13.)

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[35]Ibid., p. 1-3

[36]"DSM: Growing Acceptance, Increased Utility Spending. (Electrical World, January, 1993), p. 64.

These figures represent the best market projection figures available on GSHP although admittedly, they miss large commercial and multi-family markets.[37] The studies project the impact that strong, well funded, utility DSM programs would have on the market; the reduction in airborne pollutant emissions from more widespread use of the technology; the potential of GSHPs in five different climate zones; and the energy savings that would be realized by using the product more widely.

Exhibit 3.13. Advanced Electric Heat Pump Market Potential: U.S. Total Year 2000 (1995-2000 Program Delivery)

EQUIPMENT	BASELINE	W/ PROGRAM	NET PROGRAM EFFECT
CLIMATE ZONE 1 TOTAL GSHP MARKET	4,121	10,746	6,625
CLIMATE ZONE 1 TOTAL ASHP MARKET	3,654	15,668	12,015
CLIMATE ZONE 2 TOTAL GSHP MARKET	22,711	43,045	20,334
CLIMATE ZONE 2 TOTAL ASHP MARKET	13,838	63,678	49,840
CLIMATE ZONE 3 TOTAL GSHP MARKET	18,306	72,826	54,521
CLIMATE ZONE 3 TOTAL ASHP MARKET	4,836	103,847	99,012
CLIMATE ZONE 4 TOTAL GSHP MARKET	14,494	89,407	74,914
CLIMATE ZONE 4 TOTAL ASHP MARKET	520	127,686	127,166
CLIMATE ZONE 5 TOTAL GSHP MARKET	25,639	78,986	53,347
CLIMATE ZONE 5 TOTAL ASHP MARKET	9,624	111,249	101,624
TOTAL GSHP MARKET	85,270	295,011	209,741
TOTAL ASHP MARKET	32,472	422,128	389,656
TOTAL KWH Avoided	4,163,157,382	23,346,308,188	19,183,150,806
Winter MW Avoided	2,653	17,935	15,281
Summer MW Avoided	3,187	25,085	21,897
Gal. Oil Avoided	10,122,073	77,064,356	66,942,282
CO_2 Avoided (MT)	3,744,761	17,239,001	13,494,240
NO_x Avoided (MT)	9,977	45,307	35,330
SO_2 Avoided (MT)	15,457	70,464	55,007

Source: "Space Conditioning: The Next Frontier," (United States Environmental Protection Agency, April 1993), EPA 430-R-93-004 p. 2-3.

[37]Ibid., p. 4-3

This is the most complete text of the thesis available. The following page(s) were not included in the copy of the thesis deposited in the Institute Archives by the author:

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Most large construction/engineering companies with expertise in HVAC design and installation could develop an expertise in GSHP even though the technology associated with designing and installing GSHP systems is somewhat specialized. For large commercial projects, there are many contractors and designers with the necessary expertise to design and install GSHP systems even though they might initially require outside expertise more familiar with the intricacies of GSHP design. In terms of construction, the ground-loop portion of a large commercial project could be subcontracted to a company with expertise in well drilling and excavation work of which there are many in the US.

For residential installations in the US, there is little reason to indicate that the more general characteristics of the construction market would not be replicated in the GSHP market. This would mean a high degree of fragmentation; a large number of local or regional firms; and relatively low entry barriers. There are already a large number of contractors in the Southern U.S. who are capable of installing GSHP systems and there is little indication that their numbers will not increase if the market grows significantly.

The major problem to date with contractors and designers entering the GSHP market has not been market barriers but more an unwillingness to use a new technology that does not have a long history of proven reliability. As the engineering, architectural, and construction professions familiarize themselves with the advantages of using GSHPs for certain applications this situation will certainly change.

For the reasons stated above, the "threat of new entrants" is considered high which is an unfavorable aspect of this technology.

3.6.1.2. Bargaining Power of Buyers

There is little to indicate that the current market in the U.S. would be any different for an engineering/construction firm providing design and installation services of GSHP systems than it would be for other types of HVAC systems. Although the work of designing and installing a GSHP system is somewhat specialized, there are certainly enough contractors providing design and installation services of GSHP systems that the buyer would be able to choose from a number of different companies supplying competitive bids. This situation gives the buyer definite advantages in the marketplace when seeking concessions from contractors on prices for products and services. Many contractors are willing to take lower profit margins in today's slow construction market than they would have five years ago.

Another major consideration in analyzing the power of buyers in the GSHP market, is the effect large-scale utility purchasing of GSHPs will have. A concerted effort by utilities to promote GSHPs to their customers as part of DSM programs could greatly expand the market. Rather than having an inflationary effect, a larger market would enable manufactures and contractors to lower prices through economies of scale and pass the savings on to the utilities' customers. This is the intent of the utilities in forming strategic alliances with manufactures and directly subsidizing their products. However, since the utilities have taken such extensive measures to develop and promote GSHP as a cost-effective, electric space-heating technology, it is unlikely that they will allow manufactures and contractors to realize excessive profits when supplying products and services to their programs.

For these reasons, the "threat of buyers" is considered moderate which creates a situation that is difficult to classify as favorable or unfavorable.

3.6.1.3. Bargaining Power of Suppliers

The current market for GSHPs in the U.S. is not large enough or expanding quickly enough to give the suppliers of products and services any real power in dictating prices. Construction/engineering firms providing design and installation services for GSHP systems would benefit from this situation. The current market conditions also do not work to the advantage of subcontractors who might supply services such as well drilling, excavation, or equipment installation to the GSHP system contractor. There are enough suppliers of the goods and services for the heat transfer subsystem that none of them can significantly influence the market.

For these reasons, the "bargaining power of suppliers" is considered low which is favorable for the GSHP system contractor.

3.6.1.4. The Availability of Substitutes

As mentioned in earlier sections of this chapter, there are numerous substitutes available for GSHP systems that significantly effect the competitive nature of the GSHP market. Most of these products have significantly lower initial costs and they are often more familiar to HVAC engineers and contractors. This situation is changing slowly, but the "availability of substitutes" significantly increases the competitiveness of the GSHP market which is considered "unfavorable" for the GSHP system contractor.

3.6.1.5. Intensity of Rivalry

The "intensity of rivalry" within the GSHP market is similar to the current competitive nature of the construction industry in the US. There is enough expertise in designing and installing GSHP systems for both commercial and residential applications, that projects can all be competitively bid. There are enough firms with recognized GSHP expertise that the competition for the work on commercial projects is quite heavy. Some of these firms are interested in developing recognition within the industry by working on several large commercial pilot projects at reduced rates. For these reasons the "intensity of rivalry" is usually heavy which is unfavorable for the GSHP system contractor.

3.6.2. Cost Effectiveness for Customers

As stated previously in this chapter the initial cost of installing a GSHP is significantly higher than installing conventional space heating and cooling systems. Most of the cost differential is in the cost of installing the thermal source subsystem which can be considerable. This initial cost differential is a significant barrier for most residential and commercial property owners who usually look for a two to three year payback period. Electric utilities are willing to invest in energy saving projects with longer payback periods as are some project owners and developers, such as Stockton State College, who may even be willing to consider the total life-cycle cost of a property when making energy saving investment decisions.

With a longer time horizon the cost effectiveness of GSHP systems for space heating and conditioning becomes much more apparent. Utilities can invest far more cheaply in energy saving GSHPs for their customers than they can in new electric generating facilities. Also, by subsidizing the installation of GSHP systems in locations where gas and oil are the dominant heating fuels, utilities can be far more competitive in capturing market share from gas and oil companies. The utilities also benefit by lowering peak demand through the substitution of more efficient GSHPs for electric radiant heat and standard, electrically-operated, air conditioning systems. The benefits to the customer of having utility subsidies for these investments are significantly lower energy costs and increased energy efficiency.

3.6.3. Suitability for Construction Industry

3.6.3.1. Planning, Design, Construction, and Maintenance

The planning phase of a GSHP installation is well suited for a construction/engineering company with expertise in HVAC system feasibility studies and building energy conservation studies. The planning stages for GSHP systems often include cost comparison between alternative systems and estimating energy consumption and savings. Since most installation of GSHP systems are being done with energy conservation as a primary goal, these aspects of the planning stage are important to the customers and utilities that will finance the projects.

The design phase of a GSHP project is also well suited for a construction company with expertise in HVAC and GSHP system design and installation. Although the GSHP serves as the air conditioning and heating system for a building, it still needs to be integrated with the rest of the building's mechanical and electrical systems.

The construction and installation of a GSHP system is typically done by subcontractors supervised by the HVAC designers and engineers. Except for the ground-loop portion of the system, there is nothing unique about GSHPs that qualified heating and air conditioning installation contractors could not do. Installing the heat pumps, ductwork and piping are standard construction tasks that are routinely performed in many buildings.

The maintenance of a GSHP system is also a routine building maintenance task that can be performed by qualified personnel. Maintenance work is usually performed by the installation contractor during the warranty period. Following this, the maintenance work is typically performed by service personnel that may or may not be associated with the contractor. One of the favorable aspects of GSHPs is their low maintenance which is one indication that a large market will not develop for a GSHP system contractor in this area.

3.7. Investment Requirements

3.7.1. Research and Development Costs

The investment requirement for a construction/engineering firm that is entering the GSHP system and installation market would not be that significant. Most of the R & D work being done is funded by federal agencies, DOE and EPA, and trade organizations such as EPRI and the Rural Electric Cooperative (REC). This work has included both market and feasibility studies on GSHPs and research on the thermal source and heat transfer subsystems. A literature search has produced no evidence of proprietary R & D work being done by installation contractors other than that mentioned earlier on developing new ground loop configurations and installation methods.

Another development cost that a firm would have is the training and licensing costs of design and installation personnel. The IGSHPA offers courses for contractors and designers on soil heat transfer properties and proper installation techniques.[40] Certifications and licenses are issued for completion of these courses.

3.7.2. Government Aid

Government aid is limited to the federally subsidized R & D efforts mentioned earlier in this report. There has also been some federal support for the construction and installation costs on several large commercial projects including the State Capital building in Oklahoma. These funds were provided through the DOE as part of the Oil Overcharge Rebate Program. It is difficult to estimate how much government aid will be available to promote the use of

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[40]Heat Pumps for Northern Climates, EPRI Journal, September, 1991, PP. 32-33.

GSHPs in commercial applications since it is usually allocated on a case-by-case basis for demonstration projects.

Changing government energy policies such as the introduction of an "energy tax," might result in an increase in government aid to overcome some of the market barriers that face higher-cost energy efficient products.

3.7.3. Capital Costs

There are no large capital costs required for a construction company to enter the GSHP system construction and installation market.

3.8. Case Study: Stockton State College

3.8.1. Introduction

Large commercial applications of GSHPs in the US have been fairly limited for three basic reasons; the high initial costs of the system, a lack of awareness among engineers and designers, and a lack of good guidelines and standards for commercial applications. However, as commercial applications increase in size and number, the benefits of the high system efficiency, low energy demand, high comfort, simplicity and low maintenance should become apparent to more engineers and designers.

The largest application of GSHP in a commercial building in the US, and probably in the world, is now under construction at Richard Stockton State College in New Jersey. It provides an excellent case study for this technology for several reasons. The designers of the system have benefited from knowledge gained in the industry from several other commercial projects and because Stockton State is attempting to make this system a major test case for GSHPs in commercial buildings. (see Appendix 3.1. for a site plan of the installation)

3.8.2. Goals of the Project

Richard Stockton State College (RSSC) officials, Atlantic Electric (AE), and the New Jersey Department of Environmental Protection & Energy (NJDEPAE) have six goals for this project which are:

- Preserve the State's Capital Investment
- Materially Reduce Energy Consumption
- Strengthen the Quality of the Environment
- Achieve Substantial Cost-Containment Savings
- Demonstrate Private and Public Sector Partnership
- Provide a Model to Demonstrate the Application of an Alternative Energy Source

3.8.3. Background Information

The college is an undergraduate institution of arts, sciences, and professional studies located on a 1,600 acre campus in Pomona, New Jersey. The main campus facilities consist of over 357,000 gross square feet (GSF) of educationally-related space in a number of buildings that are interconnected by an enclosed walkway.

The GSHP system is to replace an existing HVAC system consisting of 72 rooftop gas-fired/DX multi-zone heating/air conditioning units manufactured by Nesbitt and Lennox. These units have passed their useful life; maintenance and operating expenses are excessive; and spare parts are difficult to find. The HVAC engineering firm, Vinokur Pace Engineering Services, Inc. of Jenkitown, New Jersey, did a study of the life cycle-cost of various systems and concluded that GSHPs with AE and NJDEPE rebates had the greatest cost saving potential.

3.8.3.1. GSHP System Description

The 72 HVAC units that are being replaced heat, ventilate, and air condition 357,000 GSF of educational, laboratory, and office space in three buildings. Currently, the heating is provided by indirect-fired gas furnaces and refrigeration is provided by three compressors supplying DX cooling coils. These units will be replaced with rooftop-mounted heat pumps that will attach to the existing ductwork and electrical systems. Variable air volume (VAV) zone boxes will be used to mix return air with supply air and to maintain the comfort in the building. The heat pumps will be controlled by Direct Digital Control microprocessors as part of a new energy management system for the buildings.

The rooftop GSHPs will be supplied with water from a twelve inch waterloop that runs throughout the buildings. Each GSHP is connected to the loop with a supply and return line. Since the core of the building will usually be in a cooling mode even when heat is required at the perimeter, the computerized control system can "dump" heat from the core to the perimeter. This is accomplished by opening valves in "short circuiting" loops which interconnect various parts of the main loop. This can save substantial amounts of energy by heating the water in the main loop using the excess heat in the building's core without pumping water through the ground loop. In fact, this flexibility is one of the major benefits of using heat pumps versus conventional heating and air conditioning units which can only function as a heater or an air conditioner.

The most ideal method for conditioning a space would be to have a separate heat pump for each zone in the building. At RSSC, this would have been extremely expensive and impractical. The existing ductwork required that the zones in the building remain the same and that the rooftop GSHP units be placed in the same locations. The 72 GSHP units are being custom manufactured for this application by Trane, one of the leading manufacturers of heating and ventilating equipment in the U.S. for this application. The units are multizoned, and they range in size between 10 and 40 tons. They are scheduled for installation by helicopter during the next four months.

3.8.3.2. The Well Field

The heat pumps will be supplied by a central water loop system that will circulate water from one large well field (ground thermal source, see Appendix 1). There will be a total of 400 wells of 425 feet in depth laid out in a grid pattern with each segment containing 100 wells. The vertical ground loops will be one and one quarter inch high density polyethylene (HDPE) pipe filled with water. The supply and return lines from 20 different well clusters are connected to four inch HDPE horizontal supply and return lines that feed into the main supply and return manifolds which is housed adjacent to the well field. The supply and return manifolds are twelve inch HDPE and they are connected directly to the 12 in main loop that carries the loop water to the buildings. At peak demand, the system will deliver 3600 gallons per minute to the heat pumps located on the roofs of the buildings.

It is worth noting, that the technology associated with the use and application of HDPE piping systems which have greatly improved the simplicity and effectiveness of the ground loop were developed for the natural gas distribution industry. This fact has alleviated many of the concerns that engineers and customers of this new technology have had with installing the ground loops which would be extremely expensive and impractical to fix.

Another additional aspect of this application, is that RSSC is ideally located for a GSHP system since it is located on top of three aquifers through which the wells will be drilled. The aquifers are separated by confining beds which are water impervious and act to isolate the aquifers. Having three separate aquifers will help to prevent excessive heat buildup in the groundwater during use of the system for cooling.

3.8.4. Project Costs

Exhibit 3.14. shows the projected cost estimates for the project.

Exhibit 3.14. Ground Source Heat Pump System Cost Estimates

PROJECT COST ESTIMATE ($1000)				
ITEM				
1	CONSTRUCTION	WELL FIELD	1,523	
2	CONSTRUCTION	GENERAL	37	
		PLUMBING	8	
		HVAC	82,482	
		ELECTRICAL	132	
	SUBTOTAL		4,182	
4	CONSTRUCTION	CONTINGENCY-5%	209	
	TOTALCONSTRUCTION			4,391
5	ARCH. FEES		343	
6	MNGT. FEE		132	
7	STUDIES		36	
	TOTAL FEES			511
8	MINORITY TRAINING		21	
9	OTHER EXPENSES			21
10	CONTINGENCY-2%			99
11	TOTAL PROJECT COST			5,022

Source: Stockton State College, Ground Source Heat Pump System, Project Specifications. Vinokur-Pace Engineering Services.

3.8.5. Estimated Savings

An energy analysis of the new system was done to calculate the relative energy consumption using the Energy Load Modeler (ELM) Computer Program. This analysis was done to compare various HVAC systems with the existing systems to estimate energy and cost savings. The energy consumption data is shown in Exhibit 3.15.

Exhibit 3.15. Projected Energy Savings

Energy Savings		
Existing HVAC System		
Electrical Usage	8,427,418	KWH
Gas Usage	222,314	Therms
Geothermal System		
Electrical Usage	6,372,711	KWH
Gas Usage	50,996	Therms
Total Energy Savings		
Electrical Savings	2,054,707	KWH
Gas Savings	171,318	Therms
Total BTU Savings	41,481	MMBTU
Cost Savings		
Existing HVAC System		
Electrical Costs	818,976	
Gas Costs	120,425	
Total Energy Costs	$939,401	
Geothermal System		
Electrical Cost	599,296	
Gas Cost	27,793	
Total Energy Cost	$627,089	
Total Cost Savings	219,680	
	92,632	
	$312,312	

Source: Stockton State College, Ground Source Heat Pump System, Project Specifications. Vinokur-Pace Engineering Services.

The new system is also projected to save the college cut the maintenance cost from $158,000 to $73,000 per year. Stockton State College also estimated savings in pollution emissions equivalent to removing 450 automobiles from the road or 2100 tons of environmental pollutants.

Funding for the project will be provided according to the following Exhibit 3.16:

Exhibit 3.16. Project Funding

1.	New Jersey Bonds, Education and Competitiveness (JEC) Bond Act	$1,414,000
2.	New Jersey Energy Conservation Bond Act	$2,373,000
3.	Atlantic Electric's Rebate Program	$1,100,000
4.	Stockton State College's Capital Fund	$ 135,000
		$5,022,000

Source: Stockton State College, Ground Source Heat Pump System, Project Specifications. Vinokur-Pace Engineering Services.

3.8.6. Conclusion

When completed, the Stockton State College GSHP system will be the largest system of this type in the US. The college is making a real effort to advance the state of GSHP technology by installing a sophisticated monitoring system inside the buildings and in the wellfield. 18 monitoring wells have been drilled in the field which will be used to study the heat transfer and water flow patterns in the aquifers. There is real interest at EPRI, DOE, and the EPA on the effects that a well field of this size will have on the aquifers. Studies will also be conducted to evaluate any chemical and biological changes that might occur in the well field because of changes in water temperature. Since this is the largest application of this technology to date, the research results could have a major impact on the design and construction of all large GSHP systems for commercial applications done in the future. This is the first, large system of this type to be installed and it should provide extremely important information on the viability of GSHP for use in large commercial buildings and particularly on the technical questions surrounding the function of large wellfields.

3.9. Chapter 3 Conclusion

GSHPs represent a very promising energy efficient technology for providing space heating and cooling for commercial and residential buildings. The technology is well developed and it has proven its reliability through a decade of use in the residential sector and more recently in the commercial sector. The current market for GSHPs is small in comparison to ASHPs and gas and oil fired systems, but its overall efficiency has gained it strong government endorsement.

The GSHP system faces two significant market barriers: high initial installation cost compared with conventional systems, and the tenant/landlord relationship which prevents energy saving investments. The electric utilities which are interested in promoting this technology to reduce peak demand requirements and increase market share, will have to aggressively promote and subsidize the use of GSHP to make this technology successful.

Chapter 4: Phase Changing Materials for Heat Storage

4.1. Introduction

In the United States (US) today, 40 percent of the energy and 66 percent of the electricity is consumed in heating, cooling, lighting and operating equipment in residential and commercial buildings.[1] Producing this energy contributes 36 percent of the total US CO_2 emissions and similar percentages of many other airborne pollutants. Since 1973, energy use has been lowered 12 percent per unit of commercial building floor space and 20 percent per household through energy efficiency improvements in equipment and building design.[2] Reducing energy use saves property owners 45 billion dollars in fuel bills annually, and significantly reduces the need for new power generating plants.

One method of increasing the energy efficiency of buildings and the operating efficiency of electric power plants is through the use of heat and energy storage. This paper discusses one method involving the use of phase changing materials (PCMs) for thermal energy storage in buildings.

Energy storage is considered important for a number of reasons including; energy conservation to limit the emission of airborne wastes and to obviate the need for additional power plants; lowering overall electric-power demand and peak demand; increasing the use of passive solar energy, other renewable energy sources, and waste heat by developing simple heat storage methods with wide applicability; reducing the size of heating and cooling

[1]Rosenfeld, Arthur H., "Energy-Efficient Buildings in a Warming World," (Center for Building Science, Lawrence Berkeley Laboratories), p. 459.
[2]Ibid., p. 461.

systems in buildings; and for improving energy efficiency by lowering use of less efficient peak-generating plants.

4.2. Technology Description

4.2.1. General Description

Thermal energy storage (TES) in buildings has been practiced for many years in the US. The technology advanced considerably during the 1970s with the dramatic increase in the use of passive solar heating systems in residential and commercial buildings. Practically all the TES methods being used in the US involve three different methods: sensible heat storage (SHS), latent heat storage (LHS), and thermochemical heat storage (THS).

SHS has been the most widely used method. It involves changing the temperature of some liquid storage medium such as water, or a solid such as rock. Many systems have been developed utilizing SHS techniques where the amount of storage is simply a function of the heat capacity of the storage medium, the temperature change, and the amount of the storage material. Sensible heat storage systems of rock beds or water filled tanks have been used extensively to store heat collected in solar panels or from the core of commercial buildings.[3]

However, of the three types of thermal energy storage methods, SHS is the least efficient. It takes far less energy to raise the temperature of a material than it does to break chemical bonds or melt crystalline structures. This means that costly storage space with large amounts of storage material are required from which it is often difficult to retrieve the heat over extended periods of time.[4] SHS technology is difficult to apply in building retrofits, and

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[3]Lane, George A, "Solar Heat Storage: Latent Heat Materials, Volume I," (CRC Press Inc. Boca Raton, Florida), p. 3.
[4]Ibid., p. 3.

with lower fuel prices during the 1980s, penetration of the technology has been very limited.

The second type of heat storage method, which is the subject of this report, is latent heat storage. LHS involves the storage of thermal energy "by means of a reversible change of state, or phase change, in the storage medium."[5] Some common phase changing materials (PCMs) are either salt hydrates or paraffins. LHS is considerably more efficient than sensible heat storage. LHS is more effective at transferring heat from the cooling fluid so solar collection equipment can be run more efficiently with simpler controls. This keeps the cooling fluid at a lower temperatures as it passes through the collector which makes it more efficient. The higher storage capacity of the PCM at lower temperatures allows for significant size and weight reductions of the thermal storage unit allowing more design flexibility and lower construction costs. (see Appendix 4.1.) The systems are technically more complicated than sensible heat storage systems, but it is expected that their use will increase because of the many positive aspects of the technology.

The third type of energy storage, thermochemical, relies on the potential of the storage material to absorb and release energy as molecular bonds are broken and formed with changing temperatures. The advantages of this type of system are: the low storage temperatures of the medium; the high storage to volume ratios; long storage potential with little heat loss; and high thermal efficiency. The disadvantages of the system are: the environmental considerations involved with chemical use; the difficulty of finding stable chemicals that have no byproducts during the chemical reactions; and the difficulty of siting the storage medium. As might be expected the technologies

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[5]Ibid., p. 3.

involved with this method are considerably more sophisticated than with the other storage technologies, while the storage potential is also much greater.[6]

4.2.1.1. Latent Heat Storage Using Phase Changing Materials

During the 1970s, a great deal of research was done on PCMs because of the considerable interest in passive solar technologies and the more general interest in energy efficient building design. The commercialized PCM products and systems can be categorized by their type of containment method; bulk storage, macroencapsulation, and microencapsulation.[7]

4.2.1.2. PCM Bulk Storage

Bulk storage of PCM is very similar to other types of TES systems that use water or stone as the storage material .(see Exhibit 4.1.) A wide variety of PCMs can be used depending on the particular temperature and heat transfer requirements of the application. In these systems the container is designed for storage purposes and not as the heat transfer medium.[8] All of these systems are designed for use with hydronic heat transfer systems in large storage applications for commercial and industrial buildings. The heat-transfer surface of the PCM bulk-storage container must be extensive. A 200 gallon PCM bulk-storage tank has the same storage capacity as a 1500 gallon water tank. The heat transfer surface area must be sufficient to allow efficient thermal transfer and retrieval.

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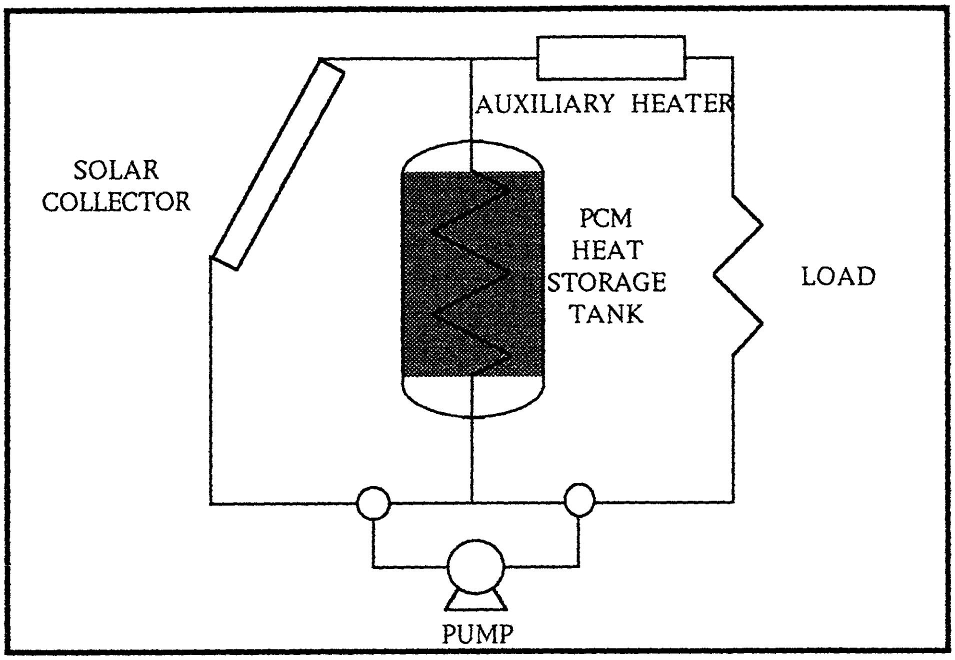
[6]Ibid., p. 5
[7]Lane, George A, "Solar Heat Storage: Latent Heat Materials, Volume II," (CRC Press Inc. Boca Raton, Florida), pp. 111-127.
[8]Ibid., p. 95.

Exhibit 4.1. Solar System Using PCM for Heat Storage with Liquid Heat Transfer Medium and Heat Exchanger



Source: Solar Heat Storage; Latent Heat Materials, Volume I.

The research and development (R&D) efforts on bulk storage of PCMs has not reached the levels of research on the other two storage methods. This may change with the increasing interest in electric demand-side management (DSM) and peak-load management for large commercial and industrial buildings for which these systems are well suited. Utility DSM programs have actively promoted TES using many other methods. It is not unreasonable to assume that PCM bulk storage, because of its high efficiency, may also be promoted by the electric and gas utilities. Many current applications where sensible heat storage systems are now used could be replaced with more efficient PCM tank systems.

Several commercial systems have been developed. These include:

- The Calmac HeatBank™ developed and manufactured by Calmac Manufacturing of Englewood, NJ.

- O.E.M. Heat Battery™ developed and manufactured by O.E.M. Products Inc. of Dover, Florida.
- TESI Storage Tank developed by Thermal Energy Storage Inc. of San Diego, California.

Dow Chemical Company is also developing a PCM bulk storage system that uses a proprietary product they have developed.

The Calmac HeatBank™ is a rotationally molded plastic storage tank approximately four feet (1.21m) in diameter by four feet (1.21) in height. A heat exchange fluid is circulated around PCM filled Calotherm™ tubes which serves to charge and discharge the PCM as needed. The O.E.M. Heat Battery™ is a nonmetallic bulk heat-storage tank filled with Glauber's salt. The heat exchange fluid is a hydrocarbon oil which comes into direct contact with the PCM. The tanks are available in sizes ranging from 60,000 to 436,000 kcal and they can be used for heat or cool storage systems. TESI Storage Tank is another bulk storage system designed for use with commercial water heating systems and active solar systems. It consists of a rectangular tank 1.21 X0.73 X 1.61 meters high (48 X 29 X 64 inches). It contains 843 litres (223 gallons) of $Na_2S_2O_3\,5H_2O$ PCM and will contain approximately 60,000 kcal of energy.[9]

All these systems are designed for TES utilizing waste heat from air conditioning, refrigeration, and industrial processing. The products are also designed for storing inexpensive off-peak electric power converted to heat, or for storing solar energy for nighttime use. There are many applications for this type of storage in commercial and residential buildings, and as engineers and contractors find more nonsolar applications, this technology should become more common.[10]

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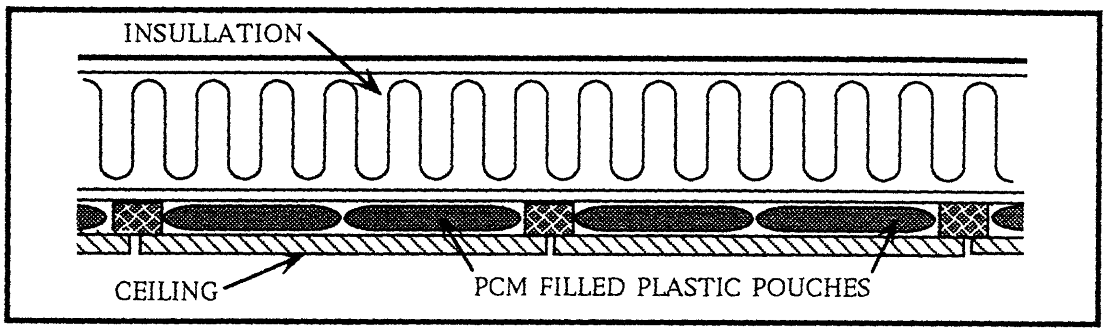
[9]Lane, George A, "Solar Heat Storage: Latent Heat Materials, Volume II," (CRC Press Inc. Boca Raton, Florida), pp. 150-152.
[10]Ibid., p. 115.

4.2.1.3. PCM Macroencapsulation

Macroencapsulation of phase change materials has been the most common type of storage method for phase change materials. This method involves encapsulating or coating the PCM in amounts ranging from several ounces to as much as 50 pounds. The most common containment material is plastic for low temperature applications and metal or films for higher temperature applications. The PCM containers can be shaped to fit particular applications which gives this method a higher degree of flexibility than bulk storage.[11] (see Exhibit 4.2.)

Exhibit 4.2. Plastic Film Pouches Filled with PCM



Source: Solar Heat Storage: Latent Heat Materials, Volume II, p. 130.

Extensive research has been done on PCM macrocapsules because of the suitability of this method for air-heat transfer in solar heating applications. A large number of products and containment methods have been developed for both active and passive storage of solar heat energy. One of the major advantages to this method is that small amounts of the encapsulated material can be integrated into the building. Larger amounts of the material can be used similarly in bulk storage systems. The major problems preventing widespread use of this technology, has been the cost of containing the PCM and incorporating it into the building. Stability problems with the PCM and

[11]Ibid., p. 116.

with the containment materials, has also been a major concern after repeated phase changes over extended periods of time have caused degradation of the containers and the PCM.[12]

4.2.1.4. PCM Microencapsulation

The third technique for containing PCMs is microencapsulation. This method involves incorporating small PCM particles into the sealed, continuous matrix of materials such as plaster, brick or plastic tile. This method is considered the most promising for several reasons. It can dramatically increase the heat storage capacity of conventional building materials while also solving the problem of containing the PCM. This could significantly lower the cost of installing the PCM in a building and eliminate the engineering and design costs of the PCM storage system. This method will also eliminate the need for additional floor space for the PCM storage systems and mechanical equipment. The major advantage to this type of system is the obvious desirability of having the PCM contained within conventional building materials. The major focus of research to date has been on solar applications in residential buildings. However, there is also a great deal of interest in using building products, primarily plasterboard, containing PCMs in commercial buildings. Concerns over fire retardation have been addressed by developing special grades of plasterboard that contain fire retardant fibers and by limiting the amount of PCM in the plasterboard.[13]

The major research efforts that have taken place in the last decade in the US have been sponsored by the United States Department of Energy (DOE)

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[12]Olzewski, M. "Thermal Energy Storage Technical Progress Report: April 1992-March 1993, ORNL/TM-12384, p. 4.

[13]Salyer, Ival, and Sircar, Anil, "Phase Change Materials for Heating and Cooling of Residential Buildings and other Applications, Proceedings of the 25th Intersociety Energy Conversion Engineering Conference, Volume 4, American Institute of Chemical Engineers, August 12-17, 1990 pp. 236-243

as part of the research on passive solar technologies.[14] The DOE sponsored research on PCM through its Solar Passive Division from 1982-1988, and since then, through its Office of Energy Storage and Distribution. R & D is continuing at the DOE's Oak Ridge National Labs (ORNL) on a variety of energy storage technologies including PCM microencapsulation.

The most promising technology being developed with the DOE involves microencapsulating the PCM in conventional wallboard during manufacturing. Extensive R & D at the University of Dayton Research Institute in this area, involved impregnating PCM in the wallboard in a post manufacturing process by dipping finished boards in a molten paraffin bath. The researchers found that up to 30% composite weight of PCM (equivalent to 90 Btu/sq. ft.) could be imbibed into the wallboard with immersion times of 10 minutes or less. The researchers also found that the PCM impregnated wallboard was strengthened and waterproofed by the process. Even though this process produced excellent results, wallboard manufacturers were more interested in incorporating the PCM in the wallboard during manufacturing. They felt that a post-manufacturing operation would be more complicated and expensive than simply adding the PCM during the manufacturing process.[15] As a result developing methods for mixing the PCM with the plaster has been the focus of more recent R & D efforts.

Research has shown that PCM within the silica matrix of the wallboard is contained by surface forces, even in a molten phase. The sharp needles of the silica provide adequate surface area and spacing for the PCM. Recent work has shown that powdered PCM can be added to silica to form a dry powder mix

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[14]Ibid., p. 236-243.
[15]Salyer, Ival, and Sircar, Anil, "Phase Change Materials for Heating and Cooling of Residential Buildings and other Applications, Proceedings of the 25th Intersociety Energy Conversion Engineering Conference, Volume 4, American Institute of Chemical Engineers, August 12-17, 1990 p. 238.

that is 60-80 percent PCM by weight. This silica/PCM mix would then be added to the wet stucco mix as a feed stock in the production process before the boards are molded.

These research efforts are directed towards developing a suitable mixture for a test production run of 200 sheets of wallboard. The effort is being planned and funded jointly by DOE through the ORNL, U.S. Gypsum (USG), University of Dayton Research Institute (UDRI), and PPG. The silica is a BXS-18 silica supplied by PPG and the PCM is a K-18 paraffin wax supplied by Witco Chemicals.

Extensive testing of the material is planned to adequately judge its performance as a building product and a heat storage material. Tests will be conducted to determine its strength, flammability, adhesive, and thermal storage properties. The tests will also include measuring the ease of cutting, hanging, finishing, and painting the product. The R & D work has included testing hundreds of different PCMs for their particular properties and selecting the most appropriate ones for microencapsulation in building materials. The most favorable PCMs are paraffin waxes refined from petroleum. These products are inexpensive; they melt at temperatures between 5°C and 70°C (41°F-158°F); they are available from most of the large petroleum companies; and they are relatively inexpensive.[16] The researchers have also developed other applications and products using PCMs both inside and outside the construction markets including; clothing and insulating wraps; heat sinks for controlling chemical reactions; and waterproofing.

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[16]Ibid., p. 240.

4.2.2. Technology Content
4.2.2.1. Effectiveness

PCM used for latent heat storage is accepted as a technology with wide potential applicability in efforts directed at developing renewable energy sources and utility demand-side management programs. PCM bulk energy storage has several clear advantages over sensible energy storage systems in terms of size and efficiency. Microencapsulation in a cost effective manner of PCM in conventional building products such as wallboard or tile, could have very wide applicability in residential and commercial buildings.

4.2.2.2. Problems & Costs

The most significant problem with PCM heat storage products is their high capital cost. Since a small market exists, manufacturers' costs are high while the high costs keep the market small. The high costs are partly due to the limited market for the products which prevents economies of scale in manufacturing. R & D has also been limited because the market is perceived to be limited. This is an old dilemma that is commonly faced by energy efficient-higher cost-products.

Increased R & D sponsored by the government and utilities could help in developing a more competitive product that would be more widely accepted. Unfortunately, there are few indications that research efforts will dramatically increase. The most promising work currently being done is the collaborative work with ORNL on developing a wallboard containing PCMs. In conversations with Mitch Olszewski of ORNL, he expressed concern that the high cost of the wallboard would prevent its widespread use outside of specialty and niche markets.[17] However, there was enough interest on the

[17] Personal Conversation, June 15, 1993.

part of the members of the collaborative to contribute to the project and perform trial production runs which is something of an indication of its potential.

The high cost and difficulty of containing the PCM in many of the older macrocontainment and bulk storage systems have also discouraged the use of PCM for many applications. The high cost of construction and concerns with liability have discouraged further use of these technologies after many of the original systems failed.

4.2.2.3. Patent Status

Most of the products and materials involved with this technology are covered by patents as might be expected. Significant amounts of proprietary R & D have been done in developing the PCMs and storage systems that companies and individuals have protected by patents. However, patents do not prevent a large construction/engineering firm from developing an expertise in designing systems incorporating PCM storage methods in constructed facilities. The role of the contractor is quite different from that of the product developer and yet their interests in promoting the use of the product are compatible.

The principles of using PCMs encapsulate in a silica matrix in conventional wallboard are patented by Ival O. Salyar at the University of Dayton Research Institute.

4.2.3. Research Groups, Companies, Organizations Developing Technologies

A large number of groups interested in solar applications for this technology performed research during the late 1970s and early 1980s. Most of the efforts have since ceased except for the work at ORNL and the University of Dayton Research Institute.

Their addresses are:

Oak Ridge National Laboratories
Engineering Technology Division
Office of Renewable Energy
Oak Ridge, Tennessee 37831

University of Dayton Research Institute
Dayton, Ohio

4.3. Regulatory and Social Acceptability

4.3.1. Legal/Regulatory Acceptability

4.3.1.1. Mandatory Technologies

This technology is not a mandatory technology. Literature searches, research, and personal conversations with research personnel do not indicate that any impending government regulations would make it mandatory.

4.3.1.2. Permitting

The principles of thermal energy storage are quite well accepted by the regulatory and permitting authorities in the construction industry. Some bulk sensible heat storage systems have been in use for many years in both commercial and residential buildings. The major concern with permitting latent heat storage systems using PCM is not with the actual principles behind the technology but more with the potential flammability of the particular PCM being used.

This aspect of PCMs is less of a concern with bulk storage systems and macroencapsulation methods in which the PCM is somewhat isolated from flame and heat sources in the event of a fire, than it is with the microencapsulation methods. Flammability is one of the primary concerns with impregnating wallboard, especially since wallboard is considered an important material for fireproofing buildings. Fire safety codes in commercial buildings are especially strict and a considerable amount of research has been directed at meeting these requirements with a wallboard containing PCMs.[18]

4.3.2. Associated Liability

The major liability aspects of using a PCM thermal energy storage system are failure of the system to work properly or some unforeseen toxic or flammability problem.

Research and practical applications over the past fifteen years have yielded a great deal of information regarding the suitability of PCM for TES in particular situations using different methods. The failure of many different bulk storage and macroencapsulation methods has led to the more recent interest in microencapsulation. The difficulty with macroencapsulation has been to maintain the integrity of the container which is subject to cyclic thermal stressing over long periods of time. Many of these early systems experienced containment failure which has increased interest in microencapsulation. The research has indicated that the simplicity of this method will limit potential failure and minimize the associated liability of using the technology.

Research has also led to the selection of PCMs that are considered nontoxic. Research has also indicated that flammability problems can be overcome as using the methods mentioned in the previous section of this chapter.

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[18]Salyer, Ival, and Sircar, Anil, "Phase Change Materials for Heating and Cooling of Residential Buildings and other Applications, Proceedings of the 25th Intersociety Energy Conversion Engineering Conference, Volume 4, American Institute of Chemical Engineers, August 12-17, 1990 p. 239.

4.3.3. Public Acceptability

The major factor behind the lack of public acceptability of PCMs for LHS has been the high cost of the systems, product and system failure, and lack of public awareness. If a lower cost method with wider applicability could be developed such as a wallboard containing PCMs, then the public would certainly be more receptive to the use of PCM for LHS. A major effort by electric and gas utilities to promote the use of the technology as part of DSM programs would also help to overcome the market barriers to more widespread use of this technology.

4.3.4. Political Acceptability

Literature searches and conversations with researchers indicate that the political acceptability of PCM for LHS is really not an issue with its development or widespread use. Research in the US has been supported by the DOE as part of a national energy policy that has investigated many different sources of alternative energy and energy conservation methods. The technology has especially benefited from public and private interest in solar energy and more recently from the increased interest in DSM. However, there is no indication that development of this technology will become a major focus of political bodies or that it will ever be widely debated in the political arena.

4.3.5. Related Public Health and Environmental Issues

As mentioned in previous sections of this chapter, the major concern related to public health and environmental issues is the potential toxicity and flammability of PCMs. This issue would be of considerable concern to public and regulatory agencies if the material were to be microencapsulated in a widely used building material such as wallboard. Recent research indicates that these issues can be addressed satisfactorily.

4.4. Market Characteristics

4.4.1. Market Size: Present and Future

The estimates for potential energy savings vary widely in the US. With energy standards as high as Japan's the US would save an estimated $220 billion per year in energy costs at an estimated cost of $50 billion per year.[19] However, it is much more difficult to estimate the potential market for a particular energy saving product. Well documented market barriers exist for new-higher cost-energy saving products and, in addition, the construction industry in the US is slow to accept new products for a variety of reasons.

The most promising market for PCM for LHS is microencapsulation in wallboard. Approximately 20 billion square feet of conventional wallboard are sold each year in the US.[20] Researchers at ORNL have estimated that a PCM impregnated wallboard will have a price premium of $12/ft^2 over conventional wallboard. They have estimated an incremental cost of $1,085 for a 1990 ft^2 house. A test case house in Boston had a five year payback period with utility incentives, and a six year payback period without incentives. These payback periods are well within the acceptable range for utility incentive programs, which the researchers considered promising.[21]

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[19]Rosenfeld, Arthur, H., Hafemeister, David. "Energy-efficient Buildings," Scientific American, April-1988, p. 78.
[20]Carlson, Tage. "Change in the Building Industry," Printed by the Construction Technology Laboratory, USG Corporation Research and Development, Libertyville, IL.
[21]Olzewski, M. "Thermal Energy Storage Technical Progress Report: April 1992-March 1993, ORNL/TM-12384, p. 40.

Unfortunately, trying to estimate the future potential size of the market for a product that is still under development is somewhat difficult. The results of the product test run need to be studied before any estimates are made of its potential market.

4.4.2. Time to Commercialization

PCMs as a product have been commercialized for many years. Large petroleum and chemical companies have a wide variety of PCMs available with different thermal and physical properties.

Many bulk storage and macroencapsulation systems have been developed, but very few of them have been commercially successful. A microencapsulted PCM in conventional wallboard is at least 2-3 years away from commercial introduction.

4.4.3. Nature of Competition

There are numerous alternatives to TES that utilize PCM. These include the various types of sensible bulk storage systems outlined earlier in this report as well as the wide array of other methods for peak-load management and energy efficiency. TES systems utilizing PCMs must be cost competitive with these other energy management methods. In the larger context, investments in any energy savings measures must be compared with the cost of burning inexpensive fossil fuels. In summary, to be successful TES systems utilizing PCM must compete with other energy saving and efficiency methods in a period of low energy prices. This will be extremely difficult if a low cost, standard building product such as wallboard is not developed.

4.5. Market Attractiveness to Construction Industry

4.5.1. Strategic Attractiveness

For the purpose of discussion, the market under consideration is defined as "a construction project in which thermal energy storage systems utilizing phase change materials are integrated." In this chapter, we will use Michael Porter's "five-forces model."[22] (see Chapter 2, section 2.5.5. for further definition of Porter model)

For the sake of discussing the strategic attractiveness of TES using PCM, a hypothetical situation must be created in which the market appears far more favorable and developed than it does at present. This type of exercise is not uncommon in trying to develop a sense for the strategic attractiveness of a potential market. A much larger market for TES is not unrealistic considering the potential for energy savings in residential and commercial buildings and the instability of fuel prices.

"The intensity of rivalry" within the construction and energy services industries is very high in the US. A large engineering/construction firm with expertise in heating, ventilating, and air conditioning (HVAC) design and TES using PCMs, would potentially be competing with many other firms with similar expertise. Most large construction engineering firms that have expertise in HVAC design have some expertise in energy-efficient building design. Some smaller architectural and engineering firms have specialized in designing environmentally sound buildings where energy efficiency is considered extremely important. There are also a large number of energy service companies that have expertise in this area including such large companies as Honeywell and Johnson Controls.

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[22]Porter, Michael E., *Competitive Advantage,* (New York, The Free Press, 1985)

In the future it may be possible for a large engineering/construction company or smaller company to specialize in TES for the construction industry. A company might specialize in TES in the same way that companies now specialize in HVAC, installing wallboard, or energy efficiency. However, maintaining a competitive position would be extremely difficult given the nature of the construction industry and the lack of any proprietary product or knowledge regarding its use. It is more likely that existing HVAC design firms would develop an expertise with TES. Companies might be exposed to it during the normal design process in attempting to serve the needs of a client, or by changing market patterns where more emphasis is placed on a particular aspect of a building. Expertise in other energy efficient products and methods such as chill storage or energy efficient lighting, has developed within segments of the construction industry that have the necessary expertise. For this reason "The intensity of rivalry" is considered high for TES in this hypothetical situation, which is unfavorable for this technology.

"The threat of new entrants" within an established market for TES using PCM is considered unfavorable for this technology. A large engineering/construction firm with expertise in this area would face the same "Threat of new entrants" that most firms in the construction industry now face. Since most of the proprietary knowledge regarding PCM is controlled by the products manufactures and not the construction/engineering firm designing and installing the system, new entrants could easily enter the market and compete for work. For this reason the "threat of new entrants" is considered high which is unfavorable for firms competing in this market.

"The threat of strong buyers" exercising excessive control over the market for TES using PCMs is considerable. The current climate for construction services in the US is very favorable to buyers. Since there are also a number of alternatives to TES using PCM, the "the threat of strong buyers" increasing the competitiveness of this market creates an unfavorable situation.

The "threat of suppliers" increasing the competitiveness of this industry and impacting its profitability depends to a large extent on the type of TES utilizing PCMs that would be installed in a structure. Since the potential for bulk storage or macroencapsulation to penetrate the market is quite limited given the previous market failures of these products, microencapsulation in a standardized building product seems to have the most potential. Wallboard containing a PCM material is the only product currently under development that might penetrate the market. However, It is difficult to estimate the market penetration of this product; what the demand might be; or if other manufacturers beside USG might develop similar products. Therefore, drawing any conclusion on the "threat of suppliers" to the competitiveness or profitability of a market for TES using PCM is very difficult.

"The threat of substitutes" for TES using PCM has been discussed previously in this report. Many alternatives exist that make this force unfavorable to a firm in this market.

4.5.2. Cost Effectiveness for Customers

The cost effectiveness for customers of TES has been demonstrated in many projects throughout the US. Most of these are chill storage systems that have been developed with electric utility support as part of DSM programs. R & D work at the DOE's ORNL has demonstrated that smaller-more efficient-heating and cooling systems can be installed in buildings if TES is used. The practice of oversizing equipment to meet peak design days can be eliminated by carefully integrating TES into a building's HVAC system. On a smaller scale, the cost effectiveness of using wallboard containing a PCM in residential buildings has also been demonstrated. A case study conducted by ORNL estimated that $190 could be saved in annual heating bills for a conventional house in the Boston area. With a utility rebate of $86/KW, incorporating PCM into the house would have a simple payback period of five years.

The high cost of building new power plants and running peak load generating plants has also created support for TES within the utility industry. Studies indicate that TES can be far less expensive than building new power plants, which are nearly impossible to site anyway because of adverse public sentiment.[23]

4.5.3. Suitability for Construction Industry

4.5.3.1. Planning, Design, Construction, Maintenance

A large construction/engineering firm with expertise in HVAC design and energy efficient building design could provide planning, design, construction and possibly maintenance services for TES using PCM. Since energy efficiency is a major concern in both new and existing buildings, TES using PCM might be included as part of the planning and design process in both of these markets. If wallboard containing PCMs becomes a viable product, then it might be very easy to incorporate it into an existing building as part of an energy-efficiency upgrade.

During the construction phase, a firm with expertise in TES using PCMs, could either perform the actual installation work or develop strategic alliances with other companies with the necessary expertise. One of the primary

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[2323]Olzewski, M. "Thermal Energy Storage Technical Progress Report: April 1992-March 1993, ORNL/TM-12384, p. 1.

reasons for microencapsulating PCMs in conventional building materials, is to minimize the maintenance on the TES system. It is therefore unlikely that a significant market will develop in maintaining these systems.

Planning, designing, and constructing a TES storage system in a residential or commercial building is inherently a construction related activity. All phases of the process should be well suited to companies in this industry.

4.6. Investment Requirements

4.6.1. Research and Development Costs

Funding for research and development for TES using PCMs has been provided by the DOE. Some R & D work has been funded by PCM manufactures and TES product developers such as USG. It is unlikely that construction/engineering firms would need to fund private research once a product was developed for use in buildings.

4.6.2. Government Aid

DOE has continued to support TES through the ORNL. If the results of the current tests on microencapsulation are favorable then funding will continue.

4.6.3. Capital Costs

There are no large capital costs required for a construction/engineering firm to enter this market. Some product training might be required which is not unusual for new products.

4.7. Case Study

Products and methods for TES using PCMs have been used in residential and commercial buildings since the late 1970s. As mentioned previously, the DOE has sponsored a considerable amount of R & D in this area. Most of the commercial applications involved bulk storage and macroencapsulation. Many of these systems have failed and are no longer in use because of unforeseen product and design problems which has limited the reliability and effectiveness of this technology.

The most promising application for PCM for TES at present is microencapsulation in wallboard using the techniques developed at ORNL, UDRI, PPG, and USG. This latest effort is the result of over a decade of work on TES for solar applications. In discussing the project with Mr. Mitch Olszewski of ORNL he outlined the approach they are taking regarding this project and the results they hope to accomplish.

The consortium of ORNL, PPG, USG, and UDRI was formed to develop standardized building products using PCMs for TES. The basic research work on microencapsulation of PCM has been done at UDRI under the direction of Ival O. Salyar. The work has been supported by the DOE through the Office of Renewable Energy. The researches proved the viability of microencapsulating the PCM in the wallboard in a postmanufacturing process as mentioned earlier in this report. The results of this work were promising enough that further funding became available through the DOE for work on a manufacturing process for microencapsulating the PCMs in the wallboard.

The success of this phase of project will depend on both the viability of manufacturing the PCM containing wallboard and the ability of the wallboard to meet the manufactures' specifications. A number of tests are planned including the construction of a model "room" at ORNL for testing the thermal performance of the wallboard. A later experiment might involve the construction of several model homes if funding and industry partners can be found.

One interesting aspect of the research work which Mr. Olszewski mentioned was the ability of the researchers to customize the thermal energy storage properties of the wallboard by using different paraffin. This would allow wallboards with different thermal properties to be installed in the same house on different walls to maintain the house within comfort zones and to minimize peak-energy use. This aspect of the PCMs in a wallboard is very encouraging to the researchers because it significantly increases the flexibility of the product.

The researchers at ORNL have approached microencapsulation of PCMs in wallboard with a degree of caution because of the past problems and "overselling" of PCM for TES during the early period of research into solar energy. Mr. Olszewski has been very careful to have industry participation in this research and to be realistic about the possibilities of developing a commercially successful product using this technology. However, the work at ORNL and UDRI is the most promising research being done in this area and should be followed closely because of its potential.

4.8. Chapter 4 Conclusion

TES is a very important technology because of its potential in improving the energy efficiency of constructed facilities; lowering construction and life-cycle costs of buildings; and obviating the need for new base and peak load power plants. Sensible storage facilities for both heat and chill storage are well recognized for their potential in these areas, and many more systems are being built. As utilities increase their spending on DSM programs, the market for these systems will increase and firms with expertise in energy conservation should capture a large percentage of this market.

Microencapsulated PCMs in a conventional building material may prove to be a viable product for TES. PCMs have significant advantages over other forms of TES. Construction/engineering companies with expertise in HVAC design and energy conservation should acquire expertise with this technology and promote it to meet their clients needs as one of the many ways to build a more energy efficient building.

Chapter 5: Chill Storage Systems

5.1. Introduction

This chapter will discuss various aspects of the use of chill storage systems in commercial buildings. Chill storage has become a widely used means for reducing peak-electrical demand and shifting electrical usage to off-peak time periods. The technology is expected to become much more widely accepted in the United States (US) as more electric utilities implement demand-side management (DSM) programs to promote energy-efficient and load-shifting technologies. According to the International Thermal Storage Advisory Committee, (ITSAC) there were no utilities promoting the use of thermal energy storage (TES) in commercial buildings in 1980.[1] However, by mid-1987, more than 16 utilities were offering financial incentives for TES as part of DSM programs. This increase in promotion and use of the technology is a good indication of how well the technology has been accepted by the utility industry and of its future potential. Exhibit 5.1. shows schematically the dynamics of the chill storage market.

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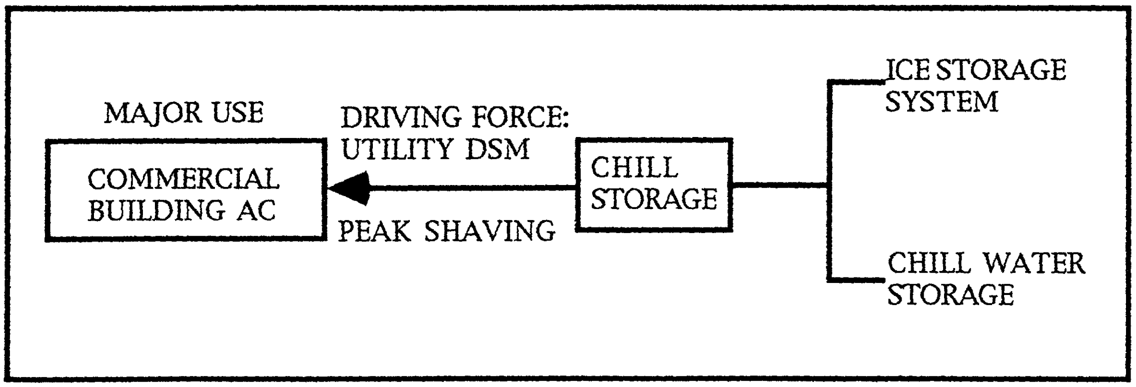
[1]Cool Storage Marketing Guidebook, EPRI EM-5841, June , 1988, p. 1-1.

Exhibit 5.1. Schematic Representation of Chill Storage Market



The major purpose behind the use of TES is to better match the existing resources of the electric utilities to the needs of their commercial and industrial customers. By using chill storage systems to shift air conditioning electric requirements to off-peak hours, utilities can better utilize existing generating, transmission, and distribution systems. The cost savings incurred by the utilities through better utilization of existing resources and by deferring construction of new plants, can be passed on to the customers in a variety of ways.

Most utilities are encouraging the use of load-shifting technologies by offering lower electric rates for off-peak usage. For example, the rate schedule for Southern California Edison includes a substantial cost difference for peak and off-peak use. (see Appendix 5.1.) Some utilities are also encouraging their customers by directly subsidizing the cost of purchasing chill storage systems at an established rate for each kilowatt shifted to off-peak use. (see Appendix 5.2.) By offering these incentives the utilities have lowered the high initial costs of chill storage systems, which has proven to be the most significant market barrier to the spread of this technology. Utility incentives and promotions have also increased awareness among building design professionals on the potentials of chill storage who many now view as an accepted technology.

Chill storage technologies are particularly attractive to utilities for promotion because of the increased usage of air conditioning (AC) in commercial and residential buildings. AC in the commercial sector currently accounts for almost 50% of the total electrical load, while it is the single largest contributor to summer peaks.[2] The increased use of computers and other appliances in commercial buildings, also requires more electrical and AC capacity during peak hours. Lower air infiltration in tighter buildings, combined with a greater emphasis on indoor air quality, has also increased AC and ventilation requirements in commercial buildings.[3] Additionally, more than 90% of new residences built in the temperate climates in the US, now have central AC systems which has also contributed to summer peaking problems even though some of this demand comes during off-peak hours . Although many newer AC systems are much more energy efficient than they were several years ago, utilities are still faced with generating expensive peak-electricity to meet demand requirements during the summer months.

This increased use of AC has further exacerbated problems for the utility industry caused by major changes in the US economy. The increasing service orientation of the economy; conservation measures; and lower electrical demand from the industrial sector, has meant increased peak-demand requirements but a lower utilization of base-load capacity. The utilities have become intent on reversing this trend without building or running expensive peaking plants which on average are 25% less efficient

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[2]"Summer Proceedings: Commercial Cool Storage, State of the Art," (EPRI EM-5454-SR, Special Report, October, 1987), p. 1-5.
[3]"Overview of Projects with Seasonal Storage for Cooling from Four Countries," Chant, G. Verne, Morofsky, Edward. (Public Works of Canada, Report # 929021), p. 4.9.

than base-load plants.[4] One of the most successful ways of doing this is through application of load shifting technologies such as chill storage.

The Electric Power Research Institute (EPRI) has estimated that 100,000 megawatts of peak electrical power demand could be shifted to off-peak through the use of chill storage technologies. According to survey results published by EPRI, many utilities have already achieved substantial cost and energy savings through the introduction of chill storage systems. [5] (see Appendix 5.3.) Unfortunately, only 425 MW of this total potential has been shifted by the nearly 2000 chill storage systems currently operating in the US. This number is expected to increase significantly as higher chill storage system efficiencies, lower costs, and increased levels of utility spending on DSM improve the potential of this technology.

5.2. Technology Description

5.2.1. Technology Content

5.2.1.1. Introduction

Over the past sixty years a wide variety of chill storage technologies have developed in the US. The two most common types of systems are ice storage and water storage systems. The emphasis of this chapter is on ice storage because of its advantage over water storage systems in terms of space requirements; higher thermal storage capacity; and recent research and development efforts that have led to increased system efficiency. The two major types of ice storage systems are "static" and "dynamic" where the

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[4]"Cool Storage: Saving Money and Energy," EPRI Journal, July/August, 1992, p. 16.

[5]1992 Survey of Utility Demand-Side Management Programs, EPRI, TR-102193, Vol. 1, pp. 33-34.

nomenclature simply refers to how the storage medium is cooled and how it is stored.[6]

5.2.1.2. Static Systems

Static systems are generally preferred over dynamic systems because they are usually smaller, simpler, more efficient, and less expensive than dynamic systems. The most commonly used ice storage systems of this type utilize "direct expansion" technology and they are very similar in design to mechanical refrigeration systems. The basic components of the system are: compressor, condenser, expansion valve, and a combination evaporator/thermal storage unit. (see Exhibit 5.2.) The thermal storage unit is a tank that contains the evaporator coils and water. During operation water freezes directly around the coils while chilled water is circulated inside the tank. When the system is fully charged, half the volume of the tank is chilled water and the other half is ice-encased evaporator coils.[7] For system efficiency, the thickness of the ice on the coils is kept below 3 inches. This prevents bridging between the coils and allows the water to circulate freely through the system.

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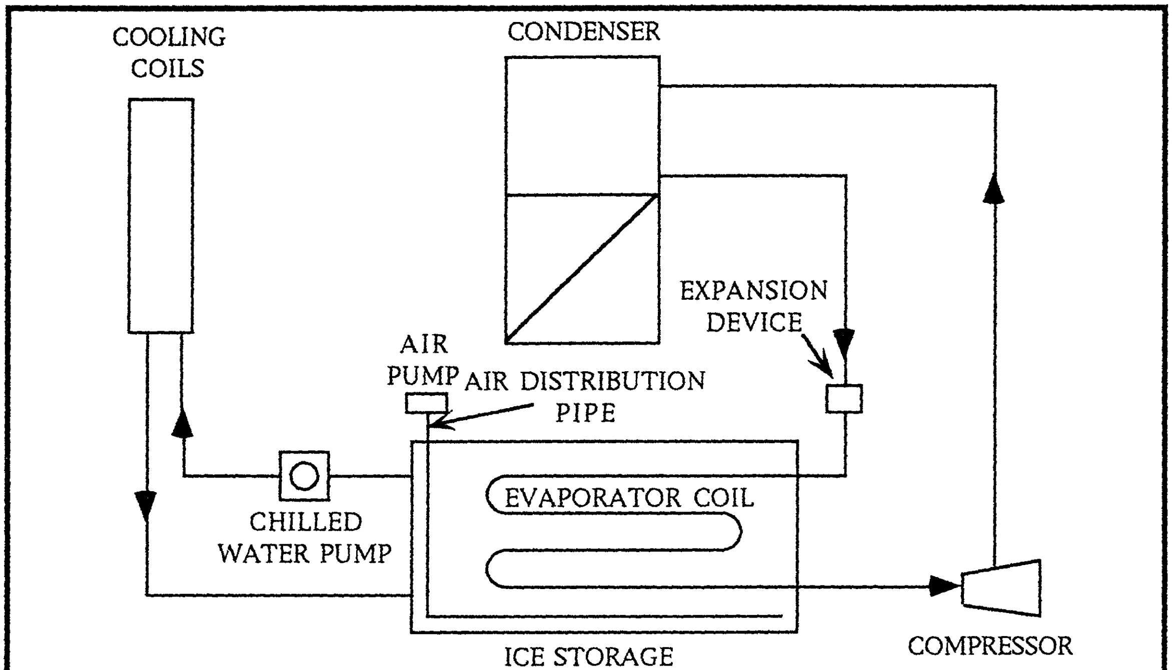
[6]"Commercial Cool Storage Design Guide," Electric Power Research Institute, EM-3981, Research Project 2036-3 (New York, Hemisphere Publishing Corporation), p. 6.
[7]Ibid., p. 6.

Exhibit 5.2. Basic Static Ice Storage Systems



SOURCE: COMMERCIAL COOL STORAGE DESIGN GUIDE

Ice storage systems are sold as packaged systems by eight major vendors in the US and they range in size from 48 to 1,200 ton hours. They are usually connected directly to a building's existing heating, ventilating, and, air conditioning (HVAC) system. Some of these systems can be equipped with heating elements for dual heat/chill storage capacity.[8]

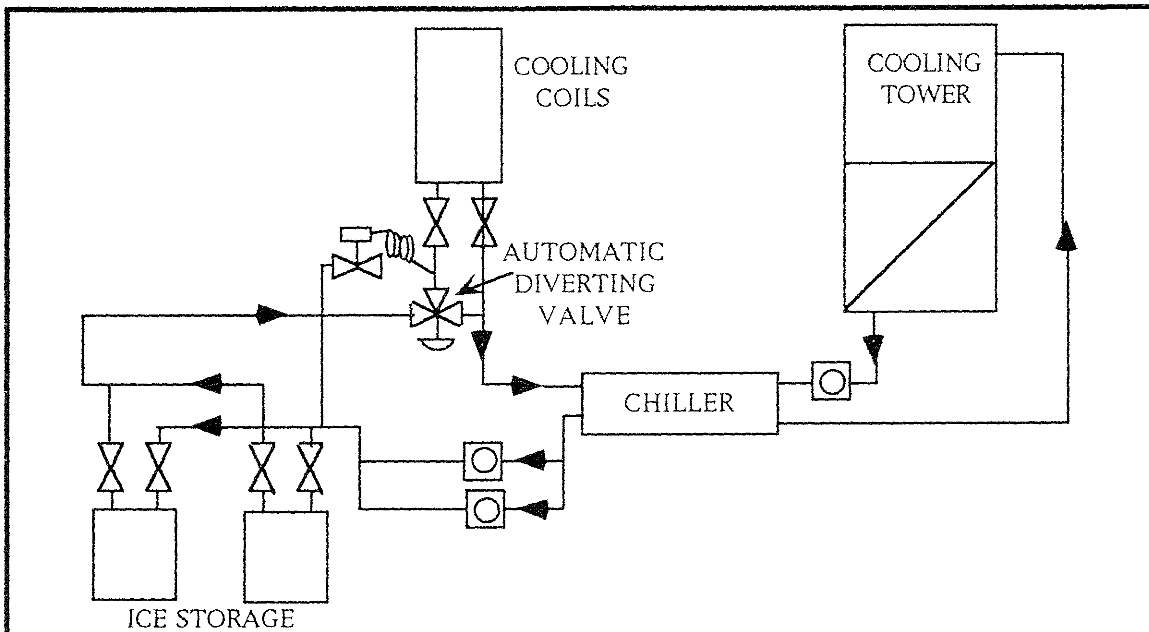
Another type of static system removes the cooling coils from direct contact with the storage medium. In the unit depicted in Exhibit 5.2.:

> "water is frozen solid around a mat of closely spaced tubes that are rolled up to a vertical position, acting as a heat exchanger. The fluid - in this case a water/glycol solution - is circulated through the tubes, entering at 25°F and coming out at 32°F. the water/glycol solution is pumped from the evaporator to the tanks during the charging cycle, removing heat from the water to cause ice to form. (in this case, the evaporator is one of three major components of a packaged chiller unit. The other two are the compressor and condenser.) The solution then returns to the

[8]Ibid., p. 6.

evaporator through the automatic diverting valve. During the discharge cycle, the ice chills the water/glycol solution which then is pumped through the automatic diverting valve. During the discharge cycle, the ice chills the water/glycol solution which then is pumped through the diverting valve to the duct coil, to cool building supply air. In comparison to the ice-builder, this system requires less storage volume, because it has a higher ice-to-water ratio."[9]

Exhibit 5.3. Modular Ice Storage System Using Brine



SOURCE: COMMERCIAL COOL STORAGE DESIGN GUIDE

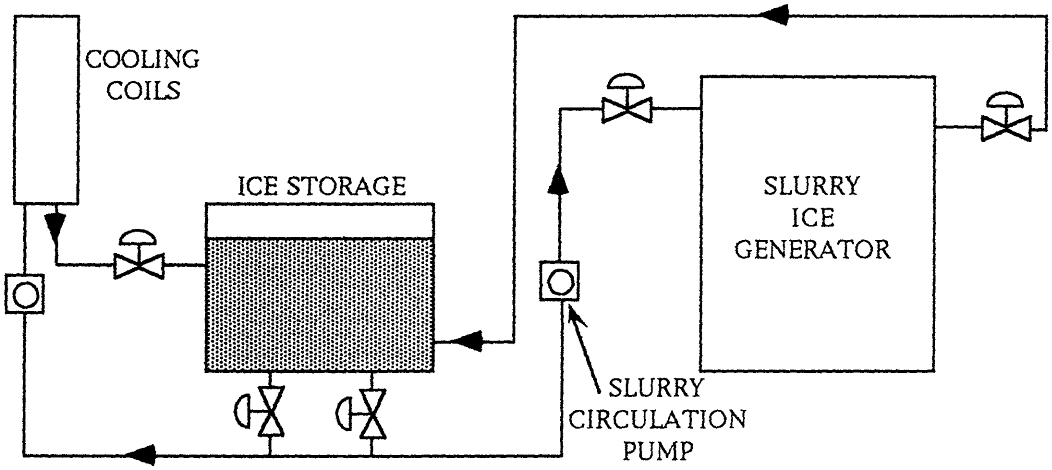
5.2.1.3. Dynamic Systems

Dynamic systems are similar to static systems in the use of basic refrigeration components. (see Exhibit 5.4.) These systems generate ice in chunk, plate, chip and slurry form during the charging cycle, which is then transported to a remote location for storage until the discharge cycle. (see Appendix 5.4.) Other systems exists which use "sprayed freezing coils" to freeze water from the storage container. Low density ice is then harvested from the coils during a defrost cycle. Since the coils are outside the storage container,

[9]Ibid., p. 8.

more of the container volume can be filled with ice.[10] The major drawback with dynamic systems is the added complexity of the equipment. Mechanical ice harvester are expensive, complicated, and difficult to maintain. The defrost cycle also adds cost and complexity to the equipment.

Exhibit 5.4. Dynamic Ice Slurry System



SOURCE: COMMERCIAL COOL STORAGE DESIGN GUIDE

5.2.1.4. Innovative Systems

With the increasing popularity of ice storage systems, a major effort has been mounted to increase the efficiency and cost effectiveness of the technology. This technology has the most potential for improvement of the three types of thermal storage; chilled water, ice, and eutectic salt. One major problem which EPRI funded research is investigating, is ice buildup on the heat exchanger surfaces which acts as an insulator and lowers system efficiency by 10%.[11] (Patent number 4907415, March 13, 1990) Similarly, in

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[10]Ibid., p. 8.

[11]"Cool Storage: Saving Money and Energy," EPRI Journal, July/August, 1992, p. 17.

dynamic systems where the ice harvesting cycle reduces system efficiency by 10% a process for minimizing ice buildup would improve efficiency.

To prevent the ice buildup on the heat exchanger EPRI developed and patented its "slippery ice process." This technology employs an additive, calcium magnesium acetate, which causes ice to form in the "liquid pool away form the heat exchanger surface, and results in a slushy type of substance that will not cling to metal.[12] This process has been tested extensively and a prototype system is being built and installed.

EPRI has also identified several other major areas for improving the efficiency of ice storage systems. The slippery ice process may obviate the need for the defrost cycle in the systems because there will be no buildup of ice on the heat exchanger. This means the system can be designed for significantly lower pressures, requiring less expensive material and allowing for increased evaporator surface in a given space. EPRI has estimated this could improve system efficiency by 5-10%. [13]

EPRI has also focused on reducing the cost and increasing the efficiency of the air distribution systems of ice storage systems. Major savings are possible because the lower temperature of the delivered air, 42-48°F compared with 55°F for conventional systems, means the size of the air distribution system's components can be reduced. Smaller fans and ducts will cost less and require less energy to operate. Overhead space can be reduced which means more floors can be constructed in a building of a given height. EPRI is also sponsoring research on new diffusers so that colder air can be introduced into a room while maintaining comfort levels.[14]

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[12]Ibid., p. 17.
[13]Ibid., p. 17.
[14]Ibid., p. 17

5.2.1.5. Effectiveness

Ice storage systems have proven their effectiveness to many utilities and customers in the US. The major benefits to the utilities are: (1) construction of expensive new generating plants can be avoided; (2) the load factor of the electric generation, transmission, and distribution systems can be improved; and (3) the overall efficiency of the electric supply system can be improved by consuming power during off-peak hours when it is cheaper to generate. Base-load power plants can be used during off-peak hours. It is also less expensive to transmit electricity at night because outside temperatures are lower.

The major benefit to the customers are: (1) energy bills can be reduced by using off-peak electricity; and (2) the cost of operating the air distribution system can be reduced because equipment components can be downsized. HVAC engineers and chill storage system manufactures have also developed many innovative methods for lowering the initial cost of chill storage systems to make the technology more competitive with conventional systems.[15]

An article published in the ASHRAE Journal (American Society of Heating, Refrigeration, and Air Conditioning Engineers) confirmed the research that EPRI has done on the potential of lowering the cost of chill storage systems. A "low temperature" air distribution system with an ice storage system was installed in an 180,000 square foot (SF) commercial office building for which the costs are listed in Exhibit 5.4.[16]

The low temperature air distribution system in the building was used after the benefits of such a system were discussed with the buildings owner. Since the ice storage system supplies air to the air handler at 50°F instead of the conventional 55°F, the supply air requirements for the building could be

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[15]Landry, Christopher, M., Noble, Craig, D., "Making Ice Thermal Storage First-Cost Competitive," ASHRAE Journal, May, 1991. p. 20.
[16]Ibid., p. 20.

lowered from 168,000 cfm to 135,000cfm. This reduction in air quantity allows for the use of smaller air handling equipment and ductwork in the building. The duct area was decreased by 20% with the lower air temperature. This reduced the cost of the sheet metal by $68,000. With an air supply temperature of 55°F, the engineers were able to specify standard insulated variable-air-volume boxes and uninsullated ductwork. Any condensation problem with the uninsullated ductwork has been alleviated by keeping the air supply temperature between 48°F and 50°F and by keeping the supply air temperature at 55°F during a two-hour cool-down cycle. This lowers the humidity in the building and has prevented condensation buildup on the uninsullated ducts.[17]

The figures of Exhibit 5.5. show that the cost for ice storage systems can be very competitive with conventional systems especially with utility rebates. Even so, the research and development effort is continuing to try to make chill storage competitive with conventional AC without using utility incentives. By 1996, EPRI has estimated that chill storage systems with heat recovery and advanced air distribution should be more efficient than conventional air conditioning equipment, although there will still be a cost premium for the equipment. (see Appendix 5.5.)

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[17]Ibid., p. 22.

Exhibit 5.5. Demand and Energy Payback Analysis for 180,000sf Commercial Building

	Hydronic-Loop Heat Pump w/ Gas Backup	Low Temp. Air Ice Storage w/ Gas Morning Warm-up
HVAC system on-peak kW	1,026	220
Yearly system consumption		
On-peak kWH	1,345,504	305,600
Off-peak kWH	707,696	1,070,000
Total	2,053,200	1,375,700
Yearly Energy Consumption		
natural gas (MCF)	845	1,219
Total demand and energy (Cost/Yr.)	$188,180	$110,606
Operating cost (Savings/Yr.)	-	$77,574
Utility rebate	-	$193,650
Total system installed cost	$1,000,500	1,325,000
Actual owner cost	-	$1,131,350
Payback	-	1.7 years

In summary, ice storage systems have proven to be a very effective technology for both customers and utilities for energy conservation and load shifting. Research efforts by various organizations directed at raising system efficiency and lowering cost through optimized designs, should continue to enhance the effectiveness of this technology.

Calmac, a leading producer of ice storage systems, has designed an ice storage system that utilizes existing rooftop air conditioning units by converting them into dynamic ice storage units. This method substantially reduces the cost of installing an ice storage system by utilizing the parts of the existing rooftop AC units which see little wear during the life of the unit. The blower and evaporator are usually in good condition because they are protected from the weather and they do not significantly contribute to the units loss of efficiency over time. The efficiency of the entire system is increased by installing an air-cooled central chiller and ice storage tanks which will obviate the need for the compressor and the condenser. The cooling coils are then modified to work with a brine solution instead of direct expansion refrigerant and a supply and return lines from the ice storage system is connected between the rooftop AC unit and the ice storage unit. The result is a chill storage system that is markedly more efficient and which delivers off-peak cooling.[18]

A new energy management system (EMS) developed for EPRI by Honeywell for controlling ice storage systems can also increase system efficiency by optimizing the controls of the equipment.[19] The EPRI/Honeywell EMS has been patented and is now commercially available. EPRI has also developed the Commercial Cool (chill) Storage Design Guide for assisting owners and engineers in sizing equipment for different buildings and in choosing the amount of storage that is most economical to install based on utility incentives and equipment costs. It is expected that all these efforts will continue to raise the efficiency of ice storage systems

5.2.1.6. Problems, Costs

The major problem limiting the growth of the market for ice storage systems is the high initial cost of the refrigeration and ice storage equipment in an ice storage system. The system is also more complex than conventional AC equipment. There are more controls and labor required for installation, which accounts for some of its higher initial cost. The other factor is that higher prices keep the market small limiting any opportunity to lower costs through economies of scale. This common dilemma with many energy saving technologies. It is difficult to determine the exact cost premium of ice storage systems over standard (AC) equipment because it can vary widely depending on the system and utility rebates. A literature search has indicated that most of the ice storage systems that are installed have a simple payback of one to three

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[18]Seminar Proceedings: Commercial Cool Storage; State of the Art, EPRI EM-5454-SR, October 1987, pp. 14-1 to 14-11
[19]Ibid., pp. 11-1 to 11-10

year for the cost premium. Even with this short payback period, the initial cost is still a problem.

Another area of concern has been the quality of the air from cold air distribution systems. The three major areas of concern are: (1) inadequate ventilation in buildings with low cooling loads and high occupancy densities because of inadequate air supplies; (2) providing adequate mixing of cold air as it enters the rooms so that "dumping" is prevented; and (3) properly insulating the pipes and ductwork to prevent heating of the air and condensation on the ducts.[20] All these issues have been addressed through research and design/installation guidelines for cool air distribution systems. It appears that these problems can be alleviated with proper design and installation procedures.

Another issue that has slowed market penetration of this technology is a general lack of awareness of the technology. Many HVAC designers, installers and maintenance personnel are unfamiliar with the equipment and its potential. This situation has already begun to change as the technology further penetrates the market.

5.2.1.7. Patent Status

A detailed patent search of the various technologies associated with ice and cool water storage has not been done. However, most proprietary technologies with significant commercial potential are covered by patents in the US. It would be safe to assume that this is the case with these technologies. A literature search for new technologies in this area indicates that they are all covered by patents. EPRI has patented its "slippery ice" technology; the

[20]"Expected Energy Use of Ice Storage and Cold Air Distribution Systems in Large Commercial Buildings," Electric Power Research Institute, CU-6643, Project 2732-16, February, 1990, p. 2-3.

hardware and software of its advanced chill storage energy controller; and its Advanced Diffuser for cool air distribution systems.

5.2.2. Research Groups, Companies, Organizations Developing Technologies

The following is a list of research groups, organizations, and companies developing these technologies.

The Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA, 94304

Calmac Mfg. Corp.
101-T.W. Sheffield Ave
Englewood, NJ 07631
(201) 569-0420

ASHRAE Research
1791 Tullie Circle, NE
Atlanta, Georgia 30329-2305
(404) 636-8400

Paul Mueller Corporation
Springfield , MO 65801
(417) 831-3000

Honeywell Home & Building Ctr. Div.
Honeywell Plaza
Minneapolis, MN 55408
(612) 951-1000

J. J. Tomlinson
Oak Ridge National Labs
Engineering Technology Division
POB Y, Bldg. 9204-1, MS-003
Oak Ridge, TN 37831

5.3. Regulatory and Social Acceptability

5.3.1. Legal/Regulatory Acceptability

5.3.1.1. Mandatory Technologies, Permitting

Ice storage systems are not considered a mandatory technology nor is there any indication from sources in the literature search or personal contact with experts in the field, that the technology will be required by government regulations. Stronger incentives for this technology might appear as part of utility DSM programs which have been required by utility regulators in many states. However, these regulatory requirements do not specifically target ice storage systems for promotion or increased use by the utilities for load management.

5.3.2. Associated Liability

A detailed literature search indicates that there are no major liability issues with using this technology. Various types of chill storage systems have been used in the US for more than 50 years without any major problems or concerns regarding liability. The various components in chill storage systems are conventional refrigeration and air conditioning components that are used widely in commercial and industrial buildings. Liability problems would more likely arise due to faulty design and installation rather than system or equipment failures.

5.3.3. Public Acceptability

There is little indication that the general public is aware enough of chill storage technologies to have formed an educated opinion regarding its acceptability. Some members of the public are aware of efforts on the part of utilities and regulators to control electrical and peak-electrical demand through DSM. In addition there is nothing to indicate that they would not support and promote the use of this technology versus the alternative of building new plants and raising electrical rates.

5.3.4. Political Acceptability

This technology, as part of the larger movement towards DSM by utilities, has a good deal of political support. It is difficult to assess the level of political awareness regarding this particular technology versus other technologies, but there are no indications from the literature search that it suffers from adverse political pressure. There is certainly political support for DSM programs which often include the off-peak discount rates crucial for this technology to succeed.

5.3.5. Related Public Health and Environmental Issues

There are no indications of serious environmental or health related concerns regarding the use of ice storage technologies. Public health and environmental advocacy groups are some of the leading proponents of DSM and peak-load management programs which they view as beneficial to people and the environment.

5.4. Market Characteristics

5.4.1. Present Market Size

The current installed market base of chill storage units in the US is 2000 units. This base is composed of chilled water, ice, and eutectic salt systems. This is not a very large number when the potential size of the market is considered, and the serious need for utility load management.

5.4.2. Future Market and Market Trends

The market for chill storage is expected to grow significantly in the future as system efficiencies increase; initial costs are lowered; and utilities become more active in supporting the technology. A large potential market for these systems certainly exists considering there are 40 million commercial AC units in existence in the US.[21] Many utilities have also recognized that ice storage systems can significantly reduce peak-demand levels and increase energy efficiency. This has provided them with an incentive to subsidize the purchasing and operation of the equipment.

Other large markets exist in retrofitting existing AC units to act as chill storage units. This can substantially lower the cost of implementing chill

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[21]"Seminar Proceedings: Commercial Cool Storage, State of the Art," Electric Power Research Institute, EPRI EM-5454-SR, Special Report, October, 1987, p. 9-1.

storage for load management purposes while increasing the efficiency of older AC units. Potential markets exist for district or regional cooling utilizing EPRI's "slippery ice" technology. EPRI is currently sponsoring research on replacing the chilled water in district cooling systems with slippery ice. EPRI has estimated this would allow a reduction in piping size and pumping energy by a factor of 4.[22] EPRI is encouraging utilities to participate in a potential new market where central cooling systems owned by the utilities would generate cooling medium at night and then sell it during the day. There seems to be little doubt that the need for less expensive AC will create significant new market opportunities for a variety of chill storage systems.

5.4.3. Time to Commercialization

There are already a wide variety of commercially available ice storage systems in the US. The technology should be considered fully commercialized even though major improvements should increase system efficiencies in the future.

5.4.4. Nature of Competition

The major source of competition for ice storage systems for air conditioning is conventional AC systems. Many of the newer, high efficiency AC systems are more efficient than current ice storage systems. Conventional systems have lower initial costs and are considered less complex than ice storage systems by design professionals. Another competitive product in the niche market for energy efficient HVAC system are commercial ground source heat pumps and several other types of thermal storage systems which include

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[22]"Cool Storage: Saving Money and Energy," EPRI Journal, July/August, 1992, p. 20.

chill water storage and aquifer seasonal storage. All of these alternatives, including commercial ice storage systems, are at present niche markets that do not represent serious competition for the makers of conventional AC equipment.

5.5. Market Attractiveness to Construction Industry

5.5.1. Strategic Attractiveness

For the purpose of discussion, the market under consideration is defined as "the construction of ice storage systems for energy conservation and peak-demand shifting in commercial buildings." A useful tool for analyzing the competitiveness or strategic attractiveness of an industry is Michael Porter's "five-forces model."[23] (see Chapter 2, section 2.5.5. for further definition of Porter model)

5.5.1.1. The Intensity of Rivalry

The current market for ice storage systems in the US is dominated by engineering firms that specialize in HVAC design and engineering. The current market is not large enough to support firms that specialize just in one area of energy storage, although some firms have specific expertise in energy-efficient building designs and equipment. The technology associated with designing, constructing, and installing ice storage systems is essentially a construction activity. The necessary expertise exists within most HVAC firms to do ice storage system design work with some outside support from specialists and technical representatives from equipment manufacturers. For these reasons, any large market that develops for ice storage systems will continue to be dominated by existing HVAC design and engineering firms.

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[23]Porter, Michael E., *Competitive Advantage,* (New York, The Free Press, 1985)

The intensity of competition for this work will be similar to the competitive nature of the general construction market. The current nature of the construction business in the US is highly fragmented and very competitive and the market for ice storage systems is similar. An additional factor to consider is the impact of utility buying of chill storage systems for DSM purposes. Most of these purchases are done in a very formal, competitive bidding process because of the regulatory requirements for strict accounting of DSM procurements. This situation exacerbates the intensity of rivalry in the chill storage market. For these reasons the "intensity of rivalry" is considered intense in this market which is unfavorable for firms trying to participate in it.

5.5.1.2. The Bargaining Power of Suppliers

There are currently eight major manufactures of ice storage systems in the US. Although this equipment is somewhat specialized, any purchasing can be done on a competitive basis. The demand for ice storage system equipment, as for most building related products in the current construction market, is not very high. This situation does not lend itself to suppliers exercising excessive control over the market or adversely affecting the profitability of contractors and engineers who are designing and installing ice storage system. For these reasons the bargaining power of suppliers is considered low which is considered favorable for firms competing in this market.

5.5.1.3. The Bargaining Power of Buyers

Buyers of equipment and engineering services in today's construction market in the US, have a strong competitive advantage when purchasing goods and services. There is a considerable amount of excess capacity in the construction industry and most work is contracted for in a very competitive bidding process. For this reason the "bargaining power of buyers" is considered high, which is unfavorable for engineering and construction firms in this market.

5.5.1.4. The Threat of New Entrants

"The threat of new entrants" entering this market should be viewed both from within the existing HVAC design and engineering market and from outside this market. For firms with existing expertise in HVAC design and engineering, there are not any significant market barriers that would prevent them from working in the market for ice storage systems. Technical information and assistance is easily accessible. Manufactures are very interested in promoting the use of these technologies by introducing HVAC designers to the benefits of ice storage systems. Therefore the "threat of new entrants" adversely affecting the competitiveness of this market is considered high, which is an unfavorable situation for the engineering/construction firm working in this market. The " threat of new entrants" from outside of the existing market of HVAC design and construction work is lower because the lack of technical knowledge in these areas would make doing this kind of work extremely difficult.

5.5.1.5. The Availability of Substitutes

Ice storage systems must be competitive with both conventional AC systems and other energy storage systems that can be used for load shifting. Savings in energy bills are usually compared with the initial costs of the different systems in a feasibility study where the load shifting ability of ice storage systems are simply reduced to a dollar value. So, although ice storage provides an additional load shifting capacity, most building owners and designers simply view this technology as a substitute for conventional AC equipment and vice versa. Ice storage systems must also compete with the other forms of chill storage which have been mentioned previously. For these reasons, "the availability of substitutes" adversely affects the competitive nature of this market which is considered unfavorable for companies trying to compete in it.

5.5.2. Suitability for Construction Industry

5.5.2.1. Planning, Design

The planning/design phase of an ice storage system requires a considerable amount of HVAC design and engineering expertise. In addition, many of these projects require knowledge of local utility DSM programs, rate structures, and utility incentives which are critical in comparing the costs of various systems. This type of work is an opportunity for construction and engineering firms to gain special skills which might be used to gain competitive advantage in emerging markets for more energy efficient building designs. However, since the current market size for this work is fairly small, this type of service could be offered in addition to conventional HVAC work.

A significant amount of planning/design work is also expected in retrofitting old HVAC systems. EPRI has indicated that this market may have the most potential for chill storage systems. As many of these older systems are replaced, building owners, HVAC designers, and utilities will be considering replacements that are more energy efficient. Firms with an established expertise in this area should have a major advantage.

5.5.2.2. Construction

Most of the construction work associated with installing ice storage systems is done by specialty subcontractors with expertise in HVAC installations. Most large construction/engineering firms maintain strategic alliances with several subcontractors and generally avoid doing this type of specialty work because of the size of the market and the special skills required.

5.5.2.3. Maintenance

Maintenance of ice storage systems and other forms of HVAC equipment is usually done by the buildings owner or HVAC contractors hired for this purpose. A large commercial contractor is usually not involved in routine maintenance of this type of equipment after construction is completed. The future market for maintenance work is expected to be moderate.

5.6. Investment Requirements

5.6.1. Research and Development Costs

The funds for researching and developing these technologies have been provided by federal and industrial research organizations that are listed earlier in this chapter. A large engineering/construction firm would not need to finance additional research to enter and compete in this market.

5.6.2. Government Aid

Currently there are no direct sources of federal funding for constructing ice storage systems for commercial buildings. Indirect federal funding of research and development work done by organizations like EPRI does exist as outlined earlier, but funding is not available for design and construction work of conventional ice storage systems.

5.6.3. Capital Costs

The capital costs for entering this market do not create any significant barrier to entry. Some funding would be needed for special training of company personnel and for acquiring technical information, but these expenses would not be excessive.

5.7. Chapter 5 Conclusion

Ice storage systems have become a well recognized method for shifting summer peak-power demands in commercial buildings. These systems act to match the existing resources of electric utilities with the requirements of their customers. The growing demand for space conditioning in commercial and residential buildings now accounts for nearly 50% of summertime peaks throughout the US. This trend is expected to continue and to create additional incentives for load shifting technologies such as ice storage. This will create market opportunities for construction and engineering firms with expertise in HVAC design, energy efficiency, and thermal storage technologies.

Chapter 6: Mined Natural Gas Storage

6.1. Introduction

Natural gas currently supplies over one third of the energy consumed in the United States.[1] Most of this is used in the highly-cyclic space heating market, but an increasing amount is being consumed by electric utilities for electric-power generation (see Appendix 6.1. and 6.2.). In 1989, the monthly gas consumption range in the United States was 1,201 billion cubic feet (bcf) in September and 2,178 Bcf in December, an almost one to two ratio between peak and nonpeak periods.[2] The natural gas supply system is not flexible enough to meet this unusual demand situation. Gas production wells are most efficiently run at a steady rate. Pipeline and distribution systems are most efficiently and economically run at full capacity. Due to the differences between the needs of natural gas consumers and producers, significant resources are being spent on developing methods for additional natural gas storage and in implementing demand-related strategies. The desired effect is to lower peak-demand through demand-side management and to carefully match storage capacity with the capacity of the natural-gas distribution networks to meet peak-demand requirements.

The need for additional natural-gas storage capacity is exacerbated by increased demand for natural gas which as gas becomes an alternative to less environmentally-attractive fuels for the electric utility industry. The

[1]Otte, C. and Kruger, P. *Introduction: The Energy Outlook in Geothermal Energy,* Stanford University Press

[2]Energy Information Administration, *Monthly Energy Review* (Washington, DC.: Energy Information Administration, February 1990), table 4.2

environmental constraints of the 1990 Clean Air Act Amendments (CAA) on the use of coal for electric-power generation makes natural gas even more attractive to power producers and environmentalists than it was previously. Industry analysts project that electric-power production will increase 5 percent to twenty percent of total gas production by the year 2000 from the current fifteen percent.[3] According to studies done by the Energy Producers Research Institute (EPRI) electricity generation is by far the biggest growth market for natural-gas usage.

A major contributing factor to increased demand by the utilities, is the supply and price stability of natural gas for the past five years. This trend is expected to continue for the foreseeable future, and some optimistic projections by the gas industry say for as long as fifty years.[4] Actual gas industry figures supporting this claim are viewed as overly optimistic by the utility industry which has been hurt by steep gas price increases in the past. Deregulation of parts of the natural gas industry certainly contributed to the current low and stable prices of natural gas. The recent price of natural gas has been more a reflection of increased competition between gas producers, than of competition with oil. Deregulation of wellhead gas prices by the federal government, and more pipeline capacity have led to greater competition and lower prices.

The other major reason why natural gas is attractive to the utilities is because it can power more efficient and less expensive generating equipment than alternatively fueled equipment. New integrated coal-gasification combined cycle (IGCC) power plants are designed to utilize both gas and

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[3]May, Ron., "Natural Gas for Utility Generation," *EPRI Journal* (January/February 1992), pp. 9.
[4]Friedman I. Steven., "The Role of Natural Gas in Electric Power Generation," 1990 to 2020," *Electric Power Systems,* Gas Research Institute, Chicago, IL,

synthetic gas made from coal. These plants are attractive because they are quickly built, cost competitive, and capacity can be increased incrementally as demand requires. They are expected to account for a majority of the increase in utility gas-fired capacity.

Many utilities have been reluctant to become overly dependent on natural gas because of the price and supply problems of the 1960s and early 1970s, and the 1978 Fuel Use Act (FUA). Increased consumption of natural gas during the 1960s and 1970s, led to serious shortages and steep price increases and the eventual passing of the FUA. The FUA encouraged the use of coal for power generation as a means of conserving gas for "better uses." Gas was viewed as too strategic a natural resource for power generation when cheap, abundant supplies of domestic coal were available.

The current situation where new plants have been designed so coal can be used as an alternative to gas if gas prices increase too dramatically, has made the utilities decision to switch to gas to meet EPA emissions standards easier. However, utility concerns still linger over the reliability of the gas distribution network to meet their requirements during periods of peak demand. Even so, most of the plants now being added by utilities and independent power producers (IPPs) as new peak load and base load power plants are fired by natural gas. They are also designed for use of synthetic gas made from coal as a backup. For utilities, natural gas is too attractive as a fuel for new capacity to ignore.[5]

The IGCC power plants represent one force behind the increased use of natural gas by power generators while environmentalists pressure for cleaner burning power plants represents another. The environmentalists see

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[5]May, Ron., "Natural Gas for Utility Generation," *EPRI Journal* (January/February 1992), pp. 12.

the potential for natural-gas fired power plants to significantly lower carbon dioxide and other airborne pollutant emissions during an interim period while alternative power sources are developed and demand-side management is implemented. CAA emission regulations are easily met with natural-gas fired power plants. Older coal-fired plants can also meet regulations by mixing natural gas with coal in the combustion cycle.[6]

The increased use of natural gas as a primary fuel for electric-power generation will mean an increased need for natural gas storage and additional pipeline capacity (see Appendix 6.3.). Additional pipelines can meet increased base load requirements while increased storage will meet the critical peak-load requirements that utilities need for reliability. So, although increased pipeline capacity will certainly help in periods of peak demand, additional storage capacity will still be of major strategic importance to meet the needs of large gas users such as utilities.

6.2. Technology Description

The use of underground storage of compressed gas has been practiced extensively in the United States (US) for many years (see Appendix 6.4.). Gas storage plays an integral role in the gas delivery system which consists of three major components: gas production, gas transportation, and gas distribution.[7] The role of gas storage is to allow for greater utilization of the gas distribution network during off-peak periods and to provide additional supply during periods of high demand. Most of the gas storage capacity in the

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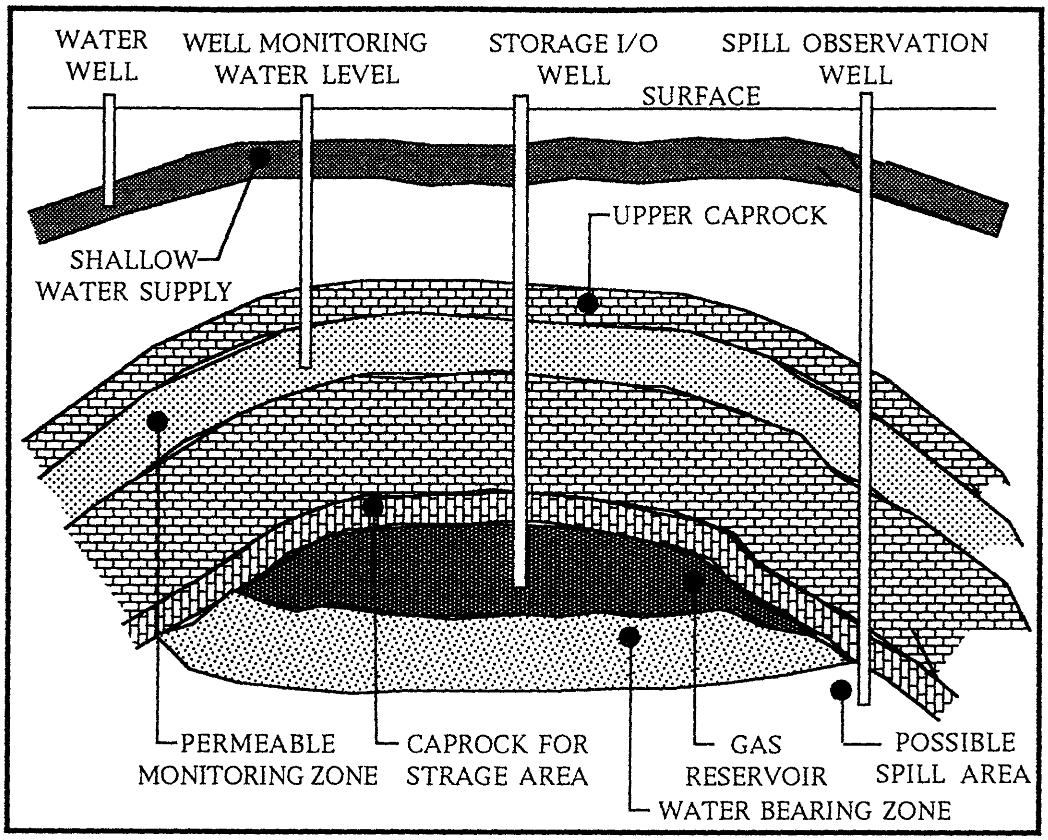
[6]Ibid.,

[7]Duann, Daniel J., "Gas Storage: Strategy, Regulations, and Some Competitive Implications." (Columbus, The National Regulatory Research Institute), September, 1990. p. 15.

US is in porous rock formations that meet the requirements for the intended use of the stored gas in terms of capacity, location, and injection and withdrawal rates. Most of these formations are depleted gas fields that have proven their adequacy for storing gas through millions of years of holding gas.[8] (see Exhibit 7.1.)

Exhibit 7.1. Typical Depleted Gas Well Storage Facility



Source: Underground Storage, Gas Engineering and Operating Series P. 57

Underground gas storage facilities are typically designed and chosen to meet either peak demand or load-leveling requirements. A peak-shaving facility requires adequate storage and deliverability capacity to meet short periods of peak demand. Load-leveling facilities are deep, large facilities with

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[8]Ibid., p. 17.

the structural integrity to hold and deliver gas over an entire season of increased demand.[9] The characteristics of both of these types of storage facilities can be enhanced through increased storage pressure; drilling additional injection and withdrawal wells; and installing more compressors. The ultimate capacity of the storage facility is dictated by the permeability and porosity of the geology of the site which limits the migration rate of the gas and the time it takes the gas to attain equilibrium pressure.[10] Depleted gas fields are the most frequently used gas storage facility. Depleted gas fields account for 295 of the 383 underground storage reservoirs in the U.S. The remaining reservoirs are located in depleted oil fields, depleted oil/gas fields, aquifers, mined salt caverns, mined coal fields and other similar facilities.

Underground storage in naturally occurring geological formations is currently the most economical means of storing gas in the in the US. (see Exhibit 6.2.) Most of these facilities are located in gas producing states with the highest concentration in Western Pennsylvania, Western New York, Ohio, Indiana and Michigan. Unfortunately, none of these facilities is near the large, eastern metropolitan areas that are currently reliant on natural gas for space heating needs and increasingly for electric power generation.

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[9] Ibid., p. 19.
[10] Ibid., p. 22.

Exhibit 6.2. Onsite Gas Storage Facilities Costs And Specifications

Storage Type	Unit Operating Cost ($/MCF)	Unit Investment Cost ($/MCF)	Peak Day Deliverability (MMCFD)
Depleted Reservoir	2.86	7	90
Aquifer	3.22	5	369
Salt Cavern	3.28	12	240
Mined Cavern	32.34	170	165
LNG	7.17	22	60
LPG	5.75	26	6
Remote Compressed Natural Gas	24.64	112	1.4
Remote LNG	1.76	8	8.0

Source: "Onsite Gas Storage for Industrial Customers," Shikari, Yusuf A, Storage Research, Gas Research Institute, Chicago, Illinois.

Gas producers and distributors have responded to the supply concerns of the utilities. Pipeline capacity will be increased to these areas with the expansion of the Trans-Canada pipeline; a new Iroquois pipeline from Ontario through New York to Connecticut; and the expansion of the Tennessee and Algonquin pipelines (see Appendix 6.5.). Unfortunately, the next generation of power plants will not only require additional pipeline capacity, but also an increasingly sophisticated type of service from the gas distributors. The utilities expect higher quality gas; consistent supply pressures; and higher quality operating characteristics than the typical gas distributor is accustomed to providing. Increased natural-gas electric power generation will require a greater degree of coordination between the gas distributors and the utilities than these organizations, which often compete in different markets, have had in the past. The utilities will also require increased storage capacity closer to the metropolitan areas in the Northeastern US for peak-shaving requirements to feel sufficiently secure.[11] These additional storage requirements have meant an increasing amount of interest in mining underground storage capacity that meets the location and size requirements of the gas distributors.

6.3. Technology Content

The use of underground storage for natural gas in mined caverns has never been attempted in the US. However, the technologies needed for designing, constructing, and operating a mined natural gas storage facility (MNGSF) are well developed and experience with constructing mined liquefied petroleum gas (LPG) storage facilities is transferable.[12] Several European countries, particularly in Scandinavia, are doing a considerable amount of research and prototype development using this technology. These countries possess few naturally occurring gas storage sites while the geology of the region is considered suitable for mined storage. The work being done in Scandinavia verifies the feasibility of constructing MNGSFs in certain areas of the US using existing technologies. [13]

6.3.1. Planning

A MNGSF has definite advantages over above ground storage of natural gas or construction of a liquefied natural gas (LNG) plant and LNG storage facility for peak-shaving requirements. These advantages include:

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[11]Smith, Douglas J., "Availability/reliability of Gas Supplies are Concerns for Utilities" *Power Engineering* (August, 1992), p. 43.
[12]Lindblum, U.E., "Storage of Gases in Rock Caverns," (Rotterdam, Balkema 1989), p.20.
[13]Ibid., p. 15.

1. The above-ground installation consists principally of a compressor station, which leaves the landscape virtually intact.

2. High injection and withdrawal rates permit recycling of the cavern volume a number of times each heating season. This creates attractive economics for cavern usage.

3. Hazards associated with earthquakes are less severe for underground facilities than for above ground facilities. This feature should be attractive for countries with frequent earthquakes such as Japan.[14]

An additional consideration for the use of MNGSFs is the difficulty of siting new LNG plants and storage facilities. Public and regulatory pressure against siting new facilities in the densely populated areas where they are most needed has increased according to engineers from the Brooklyn Union Gas Company. MNGSF may become the best option if existing LNG facilities must be closed or prove inadequate in meeting demand without the possibility of being expanded.

A basic MNGSF consists of caverns and shafts; a natural gas plant for injecting, processing, and withdrawing the natural gas; surface and subsurface monitoring equipment for pressure and gas leakage; and drains and pumps for water removal from the caverns. Exhibit 6.3. shows the two types of salt cavern storage facilities. A mined natural gas storage facility would be similar in design. The specifications for each of these components of the MNGSF is based on the expected peak-shaving requirements of the local distribution company (LDC) which is done using computer modeling of the local gas market characteristics.

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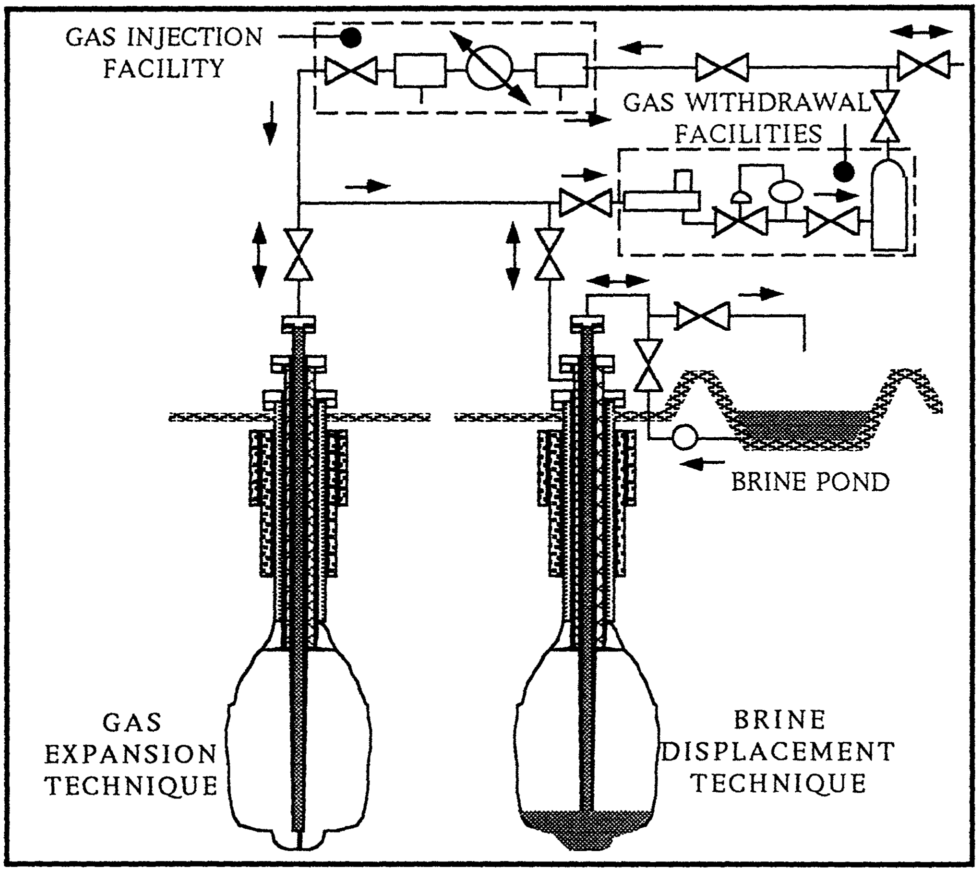
[14]Peter, Helmut W., Kucera, Milos K, "Underground Mined Cavern Storage for Gas and Electric Peak Shaving," Presented at the Osaka Gas R&D Forum 1985, p. 5.

Exhibit 6.3. Salt Cavern Storage



Source: "Salt Cavern Storage," Shikari, Yusuf, A., Joyce, Thaomas, J., Biederman, Nicholas, P., GAS/SEM.13/R.25

6.3.2. Design

Once the requirements for the MNGSF are determined, the analysis then becomes a fairly standardized exercise in evaluating the principal considerations of a site which are:

1. Geological and Hydrological conditions, including pertinent physical, chemical, and engineering properties of the host rock.
2. Logistical Conditions, including:
    2.1. Proximity to production or consumption centers and transportation networks of pipelines, roads, railways, and waterways.

    2.2. Availability, zoning status and cost of land.
    2.3. Availability of utilities.

2.4. Security of site.

3. Construction costs, dependent upon the conditions listed in "1" and "2" above, plus other factors.[15]

The most difficult aspects of the site analysis for an underground storage facility are the geotechnical and hydrological conditions that must be analyzed and considered before an actual design can be drawn. Computer modeling can simplify the important decisions that must be made in choosing a suitable depth, size, and pressure for the facility, since each of these parameters will have a significant impact on the construction costs. The parameters that need to be considered are: (1) the cost of shaft construction; (2) the cost of sealing or lining the facility; (3) the cost of the stored gas; (4) the geological formations available at various depths; and (5) the volume of the cavity and the reuse factor.[16] A suitable geological formation must meet the following requirements:

1. Adequate structural strength to allow economical mining of reasonably large openings which will remain stable for decades, with a minimum of artificial support needed.

2. Resistance to deterioration by humid air and ground water to assure long-term stability of cavern workings.

3. Low permeably which will prevent major ground water inflow into the cavern and leakage of stored product.

4. The presence of stable and favorable ground water conditions which will remain dependable throughout the planned lifetime of the cavern to assure containment of the stored product within the cavern.

5. The absence of detrimental physical and chemical reactivity between the stored product and the cavern wallrock.[17]

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[15]Feasibility study by the Brooklyn Union Gas Company on the construction of a mined underground storage facility. p. 15.
[16]Description of Computer Program Developed to Evaluate Economic Feasibility of Excavated Underground Space for Gas Storage. "A report prepared for the Columbia Gas Systems Service Corporation by the Weston Group.
[17]Ibid., p. 16.

All these requirements must be met before a site can be considered acceptable for a MNGSF. The challenges presented in overcoming any serious deficiencies are significant because of the mechanical characteristics of rock and the high degree of safety that a MNGSF requires. Extensive sampling and testing of the site needs to be undertaken to determine all the geological and hydrological factors that could effect the construction and operation of the facility.[18] Extensive testing of the rock is usually performed in a laboratory environment on core samples withdrawn from test wells at the desired depth of the caverns. Laboratory work includes tests to determine the strength, gas and water permeability, hardness, thermal expansion, chemical reactivity, and gas and water immersion characteristics of the rock material.

6.3.3. Facility Design

The theory behind the storage of gasses in mined facilities, the "dynamic containment" principle, is that gas can be stored in caverns mined in pervious rock that is saturated with groundwater. The hydrostatic pressure at considerable depths below the water table prevents outward migration of the gas through the rock fractures. Gas pressures in the cavern are usually designed for pressures up to 90% of the existing hydrostatic pressure in the caverns.[19] Since the storage volume of the gas is inversely related to the storage pressure, a MNGSF must be placed at an optimized depth to take advantage of high hydrostatic pressures without making construction costs uneconomical. It is extremely important to maintain the hydrostatic pressure in the caverns to keep them gastight.

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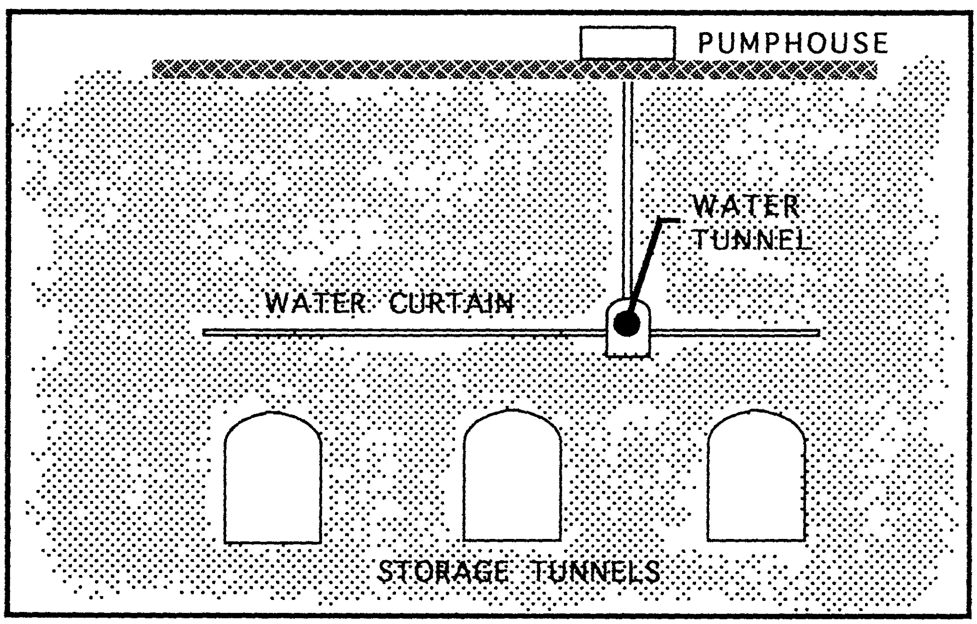
[18] Ibid., p. 6.

[19] Berest, P., "Accidents of Underground Oil and Gas Storage-Case Histories and Prevention," (Rotterdam, Balkema 1989), p.289.

Precautions are taken during the mining operation to maintain water pressure and keep the rock fractures filled with water. This can be accomplished by constructing a "water curtain" of drilled holes around the caverns that are filled with pressurized water to replace any water leaking from the rock fractures into the caverns if test results indicate insufficient naturally occurring groundwater. (see Exhibit 6.4.) Regardless of the need for any additional water to maintain the gas-tightness of the caverns, measures are taken to grout and seal any significant fractured in the rock face of the caverns. Precautions are also taken to strengthen any rock in the caverns that might break loose with the repeated changes in temperature and pressure under normal operations.[20]

Exhibit 6.4. Typical Water Curtain



Source: "The Performance of Water Curtains Surrounding Rock Caverns Used for Gas Storage," Lindblom, International Journal of Rock Mechanics, Vol 26, No. 1, pp.85-97, 1989

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[20]Witherspoon, P.A., "Gas Storage in Mined Caverns," Paper Presented at the 1974 A.G.A. Distribution Conference. p. T-156.

Completed test results of bore holes and core samples also make it possible to determine the best cavern configuration and orientation. The designers usually have a degree of flexibility in orienting the caverns to minimize the impact of the significant irregularities that occur in most rock formations.[21] Changes are sometimes made after mining has commenced to take advantage of unforeseen geological conditions that are impossible to determine from testing.

6.3.4. Construction Operations

The construction of the caverns, shafts, gas plants, and piping are conventional construction activities. The most technical aspects of this phase is the large-scale mining operation required to construct the caverns and shafts. The size and location of the boreholes must be carefully planned to minimize the high costs of shaft construction and sealing, and to optimize their location for material removal during the mining operations of the caverns. Most of this work is done using conventional mining techniques. Care must be taken to maintain the integrity of the cavern rock walls and columns during blasting.

6.3.5. Operation and Monitoring

A considerable amount of expertise has been developed on the operations and monitoring of underground and surface-gas storage facilities that is transferable to the operation of a MNGSF. The above ground facility consisting of compressors, heat exchangers, well heads, and piping is all conventional-gas storage and distribution equipment. Remote sensing devices for monitoring cavern temperature and pressure are installed during

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[21] Ibid., p. T-156.

construction. Both automatic and manual control devices are installed to control the rate at which gas is injected and withdrawn from the caverns and to maintain the pressure and temperature of the gas within the designs limits of the facility.

During initial testing of the geology and hydrology of the site, the gas tightness of the caverns is a primary concern. Any doubts about the integrity of the caverns would conceivably have been discovered early in the testing of the site and precluded further construction. However, regulatory guidelines mandate careful surface monitoring of the facility for gas leakage. Daily operations of the MNGSF includes this monitoring and routine maintenance of the equipment. This is not markedly different from monitoring other gas storage facilities and the technology is transferable and commercially available.[22]

6.3.6. Technological Developments

A considerable amount of work is currently being done on developing new technologies and methods for making underground gas storage more economical and reliable. The Research and development efforts are being conducted by the Gas Research Institute (GRI) on new cavern sealing methods to increase the reliability of and lower the cost of making caverns gas tight. New sealing methods would allow caverns to be excavated at shallower depths with lower costs that could store gas at significantly higher pressures than hydrostatic.[23] (see Exhibit 6.5. and 6.6.) GRI is also conducting research and development efforts at decreasing the cost of maintaining base gas in the

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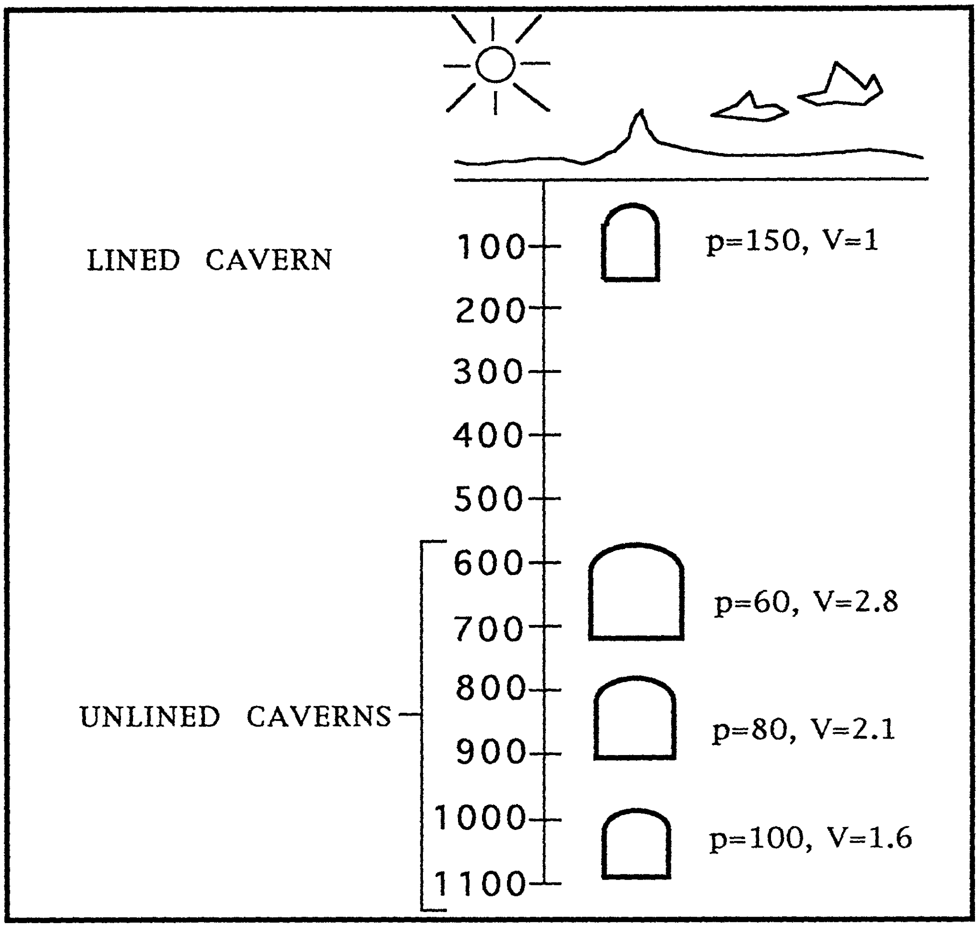
[22] Feasibility study by the Brooklyn Union Gas Company on the construction of a mined underground storage facility. p. 210.

[23] Foh, S.E., Schreiber, J.D., *Research and Development Needs for Gas Storage: State-of-the-Art-Summary,* (Chicago, Gas Research Institute, 1983), p. 20.

storage facility by developing substitutes. Since 15 to 75% of the gas in a storage facility is unusable base gas needed to maintain the pressure in the cavern, a substantial cost savings would result from substituting a less expensive inert gas such as CO_2 or N_2.[24]

Exhibit 6.5. Lined versus Unlined Cavern Depths



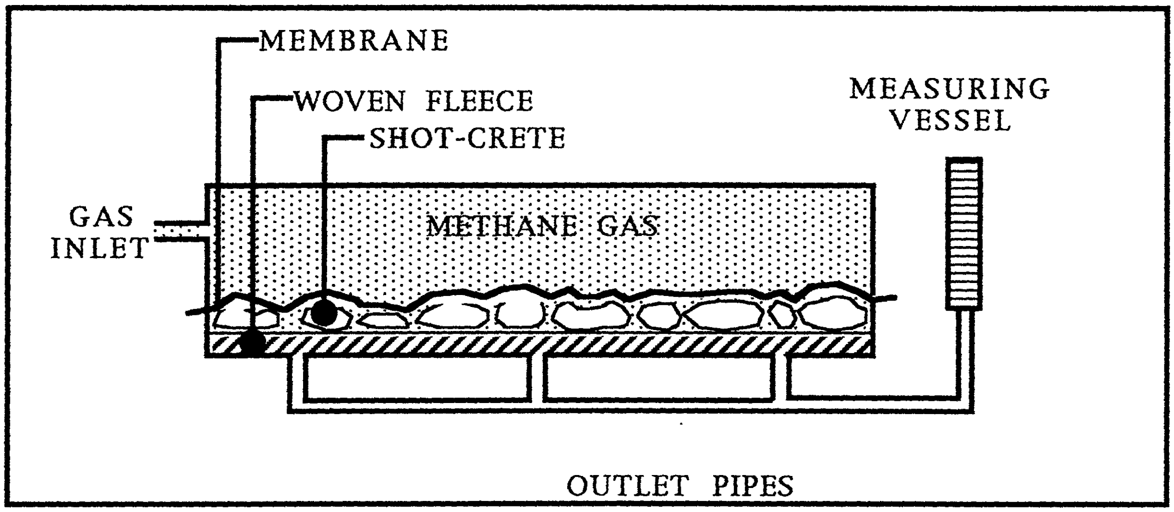
Source: "Storage of Natural Gas in Sweden," Karlson Per-Olov, SwedeGas AB, Stockholm, Sweden

A considerable amount of research and development work is being done in the Scandinavian countries in these areas also. These efforts are being undertaken because of these countries increasing reliance on natural gas and

[24]Skikari, Y.A. "Current Gas Storage R&D Programs at the Gas Research Institute," (Gas Research Institute, Chicago, 1989), 74.

because of the total lack of naturally occurring storage facilities.[25] Research there includes work on new sealing methods, water curtains, rock mechanics and prototype plants.[26]

Exhibit 6.6. Cavern Sealing Methods



Source: "Concepts for GAs Storage by Sealing Rock Caverns with Thin Plastic and Rubber Membranes," Bogdanoff, L., Dahlstrom, L.O., Department of Geotechnical Engineering, Chalmers University of Technology, Gotegborg, Sweden.

6.4. Characteristics of Technology

6.4.1. Effectiveness

Development of significant mined natural gas storage capacity would have a significant impact on the natural gas markets. The strategic implications of gas storage are well documented and these implications will become increasingly important as the gas markets are further deregulated.[27]

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[25]Saari, K.H.O. "Large Rock Caverns," *Proceedings of the International Symposium, Helsinki, Finland,* (Pergamon Press, New York, 1986)
[26]Tengborg, Per. "Storage of Natural Gas in Lined Rock Caverns-Studies for a Future project in Southern Sweden," (Balkena, Rotterdam 1989)
[27]Duann, Daniel J., "Gas Storage: Strategy, Regulations, and Some Competitive Implications." (Columbus, The National Regulatory Research Institute), September, 1990.

Increased storage capacity using MNGSFs will help to alleviate problems with supplying peak-shaving gas in the Northeastern US, and it will also help to stabilize the natural-gas supply so price spikes can be avoided.

Each segment of the natural-gas supply system, unbundled by deregulation, would benefit from increased storage capacity. The gas producers would be able to make long-term production plans with customers whose peak-shaving requirements could be met through stored gas. Pipeline companies would also benefit through better year-round utilization of the pipeline systems. Pipeline system sizing requirements could be decreased by lowering peak-demand requirements and utilizing the distribution system during low-usage periods for filling storage facilities. Large users would benefit through increased availability of natural gas during periods of high demand. This is especially important to public utilities who fear having to compete with small residential and large commercial and industrial users during periods of high demand.

6.4.2. Problems and Costs

The two major problems with increased usage and development of the technologies associated with unlined MNGSF are the lack of precedents for the use of such a facility, and the high cost of construction.

Currently in the US, no unlined MNGSFs have been built nor are any under construction. A detailed feasibility study has been done by the Brooklyn Union Gas Company which will be discussed later in this report, but this project is still in the preconstruction phase. Significant first-mover disadvantages exist in undertaking a large project of this kind even though a large number of similar storage facilities for petroleum gas have been built.

To date, the preferred method for meeting peak-shaving needs is gas storage in depleted gas fields and LNG plants. Until the cost of MNGSF becomes competitive with using depleted gas fields, MNGSF will not be used for meeting base-gas needs. It is unlikely that this will occur given the high cost differential between mining a storage facility of the required size, or using an existing field.

Use of a MNGSF for peak-shaving is more likely to occur since few naturally-occurring storage facilities exist close enough to large metropolitan areas suitable for this purpose. Currently, peak-shaving demands are met by increasing the pipeline capacity to meet even the highest demands; storing gas in pipelines under higher than normal pressure; and using above-ground LNG storage facilities. MNGSF are cost competitive with these options and may face less regulatory and public pressure during siting. It is difficult to estimate the cost of mining a GSF since it varies considerably with depth. Computer modeling is required on a site by site basis because of changing hydrology and geology.

6.4.3. Patent Status

The patenting of the technologies associated with MNGSF does not seem practical since most of the technologies are currently in wide use. A thorough literature search of the subject shows no references to patents being held or applied for in this area.

6.4.4. Research Groups, Companies, and Organizations Developing Technologies

A large number of organizations and trade groups are currently doing research on different gas storage options in the U.S. Most of the literature on the various storage methods include references to mining hard rock storage facilities as a viable method for meeting peak-shaving requirements. Organizations that are doing work of particular interest are:

1. A feasibility study for the Brooklyn Union Gas Company on constructing a MNGSF:

The Brooklyn Union Gas Company
Brooklyn, NY. 11201-3850

Fenix & Scisson, Inc.
Tulsa, Oklahoma

2. A feasibility study for constructing a dual purpose MNGSF and compressed air energy storage facility.

The Brooklyn Union Gas Company
Brooklyn, NY. 11201-3850

Fenix & Scisson, Inc.
Tulsa, Oklahoma

3. Organizations doing research on gas storage strategies and implications.

The Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631

The National Regulatory Research Institute
1080 Carmack Road
Columbus, Ohio 43201

Electric Power Research Institute
POB 10412
Palo Alto, CA 94303

6.5. Regulatory and Social Acceptability

6.5.1. Legal/Regulatory Issues

6.5.1.1. Mandatory Technologies

The use of MNGSFs are not mandatory. Gas regulators and customers do consider storage capacity extremely important because of its importance to price and supply reliability. However, with the availability of lower cost substitutes, the government has not targeted MNGSFs for any preferential treatment or particular research and development efforts. Government projects in creating strategic energy reserves have involved mined-storage facilities. Much of this technology and expertise is transferable, but the potential for MNGSFs to become a mandatory technology through government regulation is doubtful. (see Appendices 6.5. and 6.6.)

6.5.1.2. Permitting

Most state utility commissions regulate the construction activities of their LDCs. These construction regulations include the construction of storage facilities including a MNGSF. The permitting process with local environmental and public safety officials would also need to be considered in the planning of any MNGSFs. In-ground storage of all fuel products is heavily regulated in the US by a variety of agencies that would need to be convinced of the safety and merits of MNGSFs. The permitting process would involve a high level of public input. The lack of a precedents in mined-natural gas storage would certainly be cause for public concern.

6.5.2. Associated Liability

The liability of operating or constructing a MNGSF is difficult to assess because of the lack of precedents with storing large amounts of natural gas in underground caverns. Certainly the liability of constructing the facility can be evaluated through decades of work in mining, well drilling, gasline construction, and plant construction.

The major types of accidents associated with underground storage of gas and petroleum products are worth mentioning because of the similarities between the facilities and the stored materials. The three major types of failures are:

1. Loss of mechanical stability.
2. Leakage from the cavern or underground pipes to the surface.
3. Eruption or the sudden failure of the topside seals.

Failures of each type have been documented in underground storage facilities. Most of the failures have occurred in the piping and casing systems for gas injection and withdrawal. Gas migration problems have also occurred because of the failure of hydrostatic pressure surrounding a cavern allowing gas to migrate to the surface.[28] Since these cases have been documented, preventive measures should be taken during design and construction to allay public fears regarding similar occurrences.

6.5.3. Public Acceptability

Public acceptability of projects like MNGSFs in the US, is not always based on rational fears of potential accidents. Since accidents have occurred of the type mentioned previously, it is not unlikely that a certain amount of the Not-In-My-Back-Yard (NIMBY) syndrome would exist in the public acceptability of constructing and operating a MNGSF. There are obvious safety benefits to a MNGSF versus surface storage or LNG storage that the public would be aware of. However, quite often the issues of comparing the hazards or liabilities of one type of storage facility versus another, are of less interest to the public than whether new facilities are needed or wanted at all. It is this obstacle that often must be overcome in gaining public acceptability.

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[28]Berest, P., "Accidents of Underground Oil and Gas Storage-Case Histories and Prevention," (Rotterdam, Balkema 1989), p.292.

6.5.4. Political Acceptability

Political acceptability of siting MNGSFs has never been an issue because of the lack of precedents in the US in constructing and operating the facilities. The political acceptability is somewhat a function of the public acceptability and the political imperative of keeping the price of natural gas affordable and the supply dependable. This requires some regulatory oversight of the gas-delivery system and an awareness that storage systems may need to be constructed requiring government approval.

In researching this chapter, there was no report of regulatory action which discouraged the use of underground gas storage although government approval is definitely required at different levels.

6.5.5. Related Public Health and Environmental Issues

The major public health and environmental concern with storing natural gas underground is its ability to migrate into the groundwater or to the surface and into the atmosphere. The major concerns when it leaks to the surface are that it will concentrate and explode causing serious destruction and death. Cases of this happening are well documented. The other concern is the contribution natural gas makes as a "greenhouse" gas to global warming when it is leaked from wells and pipelines. This is a real dilemma for environmentalists who view increased use of natural gas as a way of lowering CO_2 emissions.

The other major concern is the effect that natural gas, stored deep underground using hydrostatic pressure, would have on the surrounding water. The general consensus is that natural gas migrating into the growing water does not pose a threat to public safety when it is dissolved in drinking water. However this could certainly be raised as an issue if significant numbers of MNGSFs were to be built in metropolitan areas that depend on ground water for drinking supplies.

6.6. Market Characteristics

6.6.1. Market Size: Present and Future

The current market for MNGSFs in the U.S. is nonexistent. Activities at this point are related to feasibility studies. One study, done by The Brooklyn Union Gas Company, will be discussed later in this chapter.

The future market for MNGSFs in the US is very dependent on future regulatory and market forces within the natural gas industry. Considering the uncertainty of the situation, future predictions are very difficult to make. According to Don Kennedy of Fenix & Scisson, the leading engineering and construction firm in the US for mined-storage facilities, there is a considerable amount of work being done in mined-hard rock storage, but nearly all of it is for LPG. Mr. Kennedy also said that all of the work that Fenix & Scisson currently does for storing natural gas is either in solution-mined salt domes or abandoned mines. Mr. Kennedy said he is not aware of any work being done on designing or constructing a MNGSF at this time in the US.

6.6.2. Market Trends

Increased need for natural gas will mean an increased need for natural gas storage. Until the costs of MNGSFs become competitive with salt domes, depleted gas fields, and aquifers, a sizable market for these facilities will not develop. The future for the market is also dependent on new pipeline construction; conservation measures; and LNG storage and production capacity. These various market forces and the responses that gas producers, pipeline operators, LDC, and end users might have are very difficult to predict.

6.6.3. Time to Commercialization

The technologies associated with constructing a MNGSF are fully developed. Further improvements in the technologies could be made that would lead to lower costs and greater efficiencies. However, it really remains for a MNGSF to be successfully built and operated before the technology can be considered fully commercialized.

6.6.4. Nature of Competition

The competition and substitutes for MNGSFs in the US are significant. For storing base-load gas, depleted oil field, aquifers, and salt domes are more cost effective than large capacity MNGSF. For peak-load storage, demand is currently being met through increased gas-pipeline capacity and LNG storage. Until the cost of constructing MNGSFs are competitive with these alternatives, or regulations are changed that encourage their development, it is unlikely that any will be constructed in the near future in the U.S.

6.7. Market Attractiveness to Construction Industry

6.7.1. Strategic Attractiveness

For the purpose of discussion, the market under consideration is defined as "the market for construction of underground compressed natural gas storage facilities in a mined hard-rock cavern." In this chapter, we will use

Michael Porter's "five-forces model."[29] (see Chapter 2, section 2.5.5. for further definition of Porter model)

The potential size of a MNGSF industry at some time in the future is very difficult to determine. As stated previously in this report, government regulations would need to be passed banning the use of substitutes before any widespread use of MNGSFs would develop. For the sake of this analysis, an assumption is being made that an "industry" has developed, and the analysis is being done of this industry.

The "bargaining power of suppliers," subcontractors, equipment manufacturers, and material suppliers is not high. These markets are currently very competitive in the US which makes their bargaining power low. The "bargaining power of suppliers" is low, which is favorable for the MNGSF contractor.

The "bargaining power of buyers," LDCs, large utilities, and pipeline companies, would be strong because of the threat of substitutes; the low profitability of these regulated industries; and low switching costs. The "bargaining power of buyers" is considered unfavorable to the MNGSF contractor.

The "threat of new entrants," other large contractors, mining companies and engineering/construction companies, is considered small. Entering this market would require considerable expertise and experience in large-scale underground cavern construction. Currently in the US, one company, Fenix & Sisson, dominates the mined-storage engineering and construction market.(see Appendix 6.7.) The company has proven that experience and learning effects access to the latest technologies; capital requirements; and economies of scale create significant barriers to entry into

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[29]Porter, Michael E., *Competitive Advantage,* (New York, The Free Press, 1985)

this market. Therefore the low "threat of new entrants" would create a favorable situation for the MNGSF contractor.

The "threat of substitutes," depleted gas fields, LNG, pipelines, and surface tank storage, are all substitutes for MNGSFs. These alternatives are currently the most significant problem with the development of MNGSF technologies in the US. The "threat of substitutes" is therefore considered unfavorable for the MNGSF contractor.

The "intensity of rivalry" in specialty or niche construction markets in the US is not as intense as in the general-construction markets. There are a limited number of large specialty contractors that could compete for work constructing MNGSFs with the required technical expertise and resources. The "intensity of rivalry" is favorable for contractors of MNGSF.

An industry analysis using Porter's "five-forces model" looks favorable for large construction companies with the required expertise entering a market for MNGSF . However, a dramatic change in the current gas-storage market would have to occur before mining natural-gas storage facilities could be considered an industry. This distinction between a hypothetical market that could develop with increased use of natural gas and changing government regulations, and a real market for MNGSFs needs to be emphasized. It is extremely difficult to analyze future markets developments for facilities that are as specialized as MNGSFs where changes in regulations or market forces can influence the viability of a project.

6.7.2. Cost Effectiveness for Customers

The cost effectiveness of storing natural gas in underground caverns is well documented. The gas producer benefits through better control of the production process. Storage can be filled during periods of slack demand and used during periods of peak demand, thereby leveling the demand at the wellhead and increasing the productivity of a gas field.

The pipeline operator benefits through increased storage because of better utilization of the pipeline during periods of low demand. Periods of low demand can be used for filling storage capacity close to the end user which can be used for peak-shaving and meeting base demand. Without this storage, the pipeline systems would be underutilized during periods of low demand and inadequate during periods of peak-demand.

Gas distributors and end users also benefit through the use of cost-effective gas storage. Storage increases the supply of gas during periods of peak demand. Without it, some customer's usage would have to be curtailed. Storage also greatly reduces the upward pressure on natural gas prices.

6.7.3. Suitability for Construction Industry

The markets for planning, designing, constructing and maintaining MNGSFs are suitable for a construction/engineering to enter that has some expertise in underground construction.

6.7.3.1. Planning

The planning of a large project such as an MNGSF is an activity that a construction/engineering company with expertise in underground construction would be well suited for. Preparation of the master plan, cost estimates, filing for permits, and preparing environmental impact statements are all construction related activities. It is important that companies interested in building MNGSF be involved in the planning of the facilities so that cost-effective systems can be proposed.

6.7.3.2. Design

The design expertise of a major construction/engineering company would be important in becoming a major participant in constructing MNGSF. A company with experience in designing high-pressure storage facilities; gas storage facilities; and underground-watertight facilities could become a competitor in the MNGSFs market. A company with proprietary knowledge or expertise in designing gas storage facilities could become a dominant player.

6.7.3.3. Construction

The construction of a MNGSFs is an activity that many large engineering/construction companies are currently capable of. Some companies have the expertise in mining, geology, hydrology, and gas storage from constructing similar facilities that could be transferred to the construction of a MNGSF. Construction expertise in tunneling, mining and other large civil engineering works with a high content of underground work, would certainly be advantageous in developing an expertise in constructing MNGSF.

6.7.3.4. Maintenance

The market opportunities for the maintenance of a MNGSF seem to be limited unless unforeseen problems arise. One of the biggest benefits to a MNGSF is the low maintenance and operating costs of the facility. Many of the maintenance operations could be done by a construction/engineering firm if the maintenance work was on the underground portion of the facility. Expertise in maintaining the above ground portion of the facility, pipes, compressors, filtering plant, and monitoring equipment would need to be acquired by the construction company. This would hardly seem worthwhile since the market would be relatively small. Most of this work has traditionally been done by the LDC.

6.8. Investment Requirements

6.8.1. Research and Development Costs

Recent research and development efforts in natural gas storage have been carried out by national trade associations such as the American Gas Association (AGA), EPRI, and the GRI. Many of these studies have been conducted by educational institutions with government subsidies because of the national strategic importance of fuel storage.

The high cost of building a prototype plant for research and development work would be prohibitive for a construction company without government or industry sponsorship. The work being done in the Scandinavian countries has been conducted with government assistance by industry and educational institutions. However, a similar effort sponsored by the US government for building a prototype MNGSF has not been proposed in the US. There are currently no government programs that construction companies could use for developing this market.

6.8.2. Capital Costs

The capital costs of entering the market for MNGSF would not be substantially different than those required for entering other heavy construction markets. Presumably most companies intent on constructing a 150 million dollar facility would be financially qualified. Large investments in plant and equipment dedicated to constructing a MNGSF, could be transferred from and to other construction or mining jobs because of their inherent flexibility. This would mean a minimal investment in equipment dedicated to building just MNGSFs. This would keep the capital costs of entering this market low.

6.8.3. Appropriability

The various technologies involved with constructing a MNGSF are construction related or easily acquired by a construction/engineering company with expertise in underground construction. Construction companies with experience in tunneling, mining, geology, hydrology, piping, and gas storage, could participate in a market building MNGSF if one develops. Companies wishing to enter the market could form strategic alliances or subcontract with companies like Fenix and Sisson that have specific expertise building underground storage facilities. However, since none of these facilities has ever been built to store natural gas, some pioneering efforts will have to be made by companies wishing to enter this market. A definite "first mover" disadvantage exists in being the first builder of a MNGSF since unforeseen problems may need to be addressed.

6.9. Case Example

As mentioned earlier in this report, most natural gas in the United States is stored in depleted gas fields, depleted oil/gas fields, and aquifers. By far, the most popular of these three is depleted gas fields. As these storage facilities filled to capacity, gas suppliers and producers began investigating manmade facilities, abandoned mines, salt domes, embedded salt layers and MNGSF. To date in the US, the only in depth feasibility study that has been done on mined natural gas storage, was performed in 1982 by the Brooklyn

Union Gas Company. This study provides the best example of the potential for mined natural gas storage to become a reality in the US.

6.10. The Brooklyn Union Gas Company

The Brooklyn Union Gas Company (BUGC) is one of the largest gas utilities in the US serving 3.6 million customers in the New York boroughs of Brooklyn, Queens, and Staten Island.[30] In the early 1980s, BUGC determined that moderate demand growth of 10.6% would lead to an increase of 18.3% in peak demand growth by the year 2003.[31] (see Appendix 6.8.) The company began studying various options for increasing its peak-demand capacity including additional LNG capacity; surface tank storage; and a MNGSF.

An unlined MNGSF represented the only method of storing a peak-demand natural gas supply that BUGC did not have previous experience with. The company owned and operated LPG plants for peak-demand gas which it replaced with LNG and synthetic natural gas (SNG) plants in the mid-1970s. BUGC currently uses only its less-expensive LNG plant to meet peak-demand requirements. BUGC estimated in 1982, that a new LNG plant would cost $160 million dollars to build which was significantly higher than a MNGSF with the same storage capacity of 700 million cubic feet. After this initial analysis was completed with the conclusion that a MNGSF was the most economically feasible peak-shaving alternative, BUGC hired Fenix & Sisson to further study this alternative. Fenix & Sisson is the leading firm in the US for the construction and engineering of mined-underground storage facilities. The

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[30]Hoffman, C.M., Lange, R.B., "An Innovative Approach to Peak Gas Storage in Large Suburban Areas-A Hard Rock Natural Gas Cavern In New York City," (Balkena, Rotterdam 1989), p. 323.
[31]Peter, Helmut W., Kucera, Milos K, "Underground Mined Cavern Storage for Gas and Electric Peak Shaving," Presented at the Osaka Gas R&D Forum 1985, p. 4.

company has designed and built most of the mined LPG storage facilities in the US. They were hired by BUGC for this well recognized expertise.

Fenix & Sisson designed a generic facility for BUGC consisting of a grid of unlined tunnels after determining the company's peak-shaving requirements using the Gas Dispatch Computer Model for the year 2003.[32] (see Appendix 6.9.) The optimal depth for the storage caverns was determined using a computer model which performed a Depth Optimization Analysis[33] comparing the costs of excavation, shafts, compressors, feasibility studies, project support, conversion and testing, engineering and construction fees, and cushion gas at various depths. (see Appendix 6.10.) The optimal depth was determined to be 2500 feet, which required an excavated volume of 976 million cubic feet. At this depth the usable capacity of the facility is 700 million cubic feet with the remaining volume required for cushion gas. The facility was designed as a grid of unlined caverns using the "room and pillar" system, where the hydrostatic pressure of the groundwater, 0.4335psi per foot of depth, effectively seals the fractures in the rock to contain the natural gas.[34] Design loads in the caverns using this sealing method are limited to 90% of the hydrostatic head of the overlying water. Operating pressures for the BUGC facility was between 75 and 900psi with a withdrawal rate of 165 million cubic feet per day.

6.10.1. The Site Selection Process

The BUGC developed a systematic site selection process consisting of four phases. The first phase consisted of an analysis of the company's distribution

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[32]Ibid., p. 8.
[33]Ibid., p. 9.
[34]Feasibility study by the Brooklyn Union Gas Company on the construction of a mined underground storage facility. p. 15.

system to determine the most effective location for the facility to be added to the network. The best areas were selected by BUGC for a second analysis by a real estate consultant that chose four specific sites using the following criteria:

- availability of 30-40 acres of land
- low population density in the surrounding area
- absence of on site structures
- zoning for heavy industrial use
- ownership by a single party
- laceration adjacent to the gas pipeline
- accessibility by barge, truck, and rail

The final selection was done by Fenix & Scisson after performing preliminary geotechnical, logistical, and economic evaluations using such criteria as environmental impact, access, mining and excavation costs, and disposal costs. The final choose was a site next to the John F. Kennedy Airport (JFKA). Preparations were made for a detailed geotechnical feasibility study to determine all the below-ground engineering factors effecting the storage facility operations and construction.

6.10.1.1. The Geotechnical Feasibility Study

The geotechnical feasibility study consisted of drilling, coring, video surveys, hydrofracturing, and hydraulic testing were done using five test holes that were drilled to 2800 feet in depth. Surveys of the test holes and analysis of the samples were done to determine the orientation and character of the discontinuities in the geology of the site. These analyses allow for proper orientation of the chambers to minimize the loss of mechanical stability of the columns caused by the discontinuities in the rock.

Core samples were withdrawn from the critical depths between 700 feet and 2800 feet for extensive laboratory testing. These tests to determine the rock properties were performed at the Rock Mechanics Laboratory of the

University of Illinois at Urbana; the US Testing Laboratory at Tulsa, Oklahoma; Terra Tek of Salt Lake City, Utah; and Dr. Bezalel C. Haimison of Madison, Wisconsin. These tests included tensile and compressive testing at different orientations to the foliation to help in designing the rock pillars or walls between the chambers for adequate structural integrity. The tests confirmed an average failure strength of 9740 psi along foliation planes for the gneiss which is considerably less than the average true intact strength of the material of 16,800psi.[35] (see Appendix 6.11.)

Studies were also undertaken on rock samples to determine the effects of operating the facility on the integrity of the rock. Simulation studies were performed to replicate the heating and cooling cycles on the rock during injection and withdrawal of the natural gas. Rock samples were subjected to temperature cycles between 40 and 160 degrees Fahrenheit and cyclic loading. The results of these tests were favorable and showed no significant reduction in the strength of the rock. Hydrologic and air/nitrogen testing of one of the holes was also done to test the permeability of the rock. These results were also favorable, which further reinforced the viability of the hydrostatic-sealing method.

The results of these tests are important because they showed the feasibility of mining a storage facility in the JFKA location and the optimal design for the facility to minimize excavation costs. These tests gave the designers the necessary information to determine the maximum cavern opening size and spacing. Larger openings allow for greater economies of scale with increased productivity because larger equipment can be used which requires less energy to mine the rock.[36]

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[35]Ibid., p. 192.
[36]Ibid., p. 192.

6.10.1.2. Cavern Construction and Cost

The cavern design that was developed by Fenix & Scisson, utilized two 6 foot diameter shafts for material delivery, rock hoisting, and personnel access, and three, 3 foot diameter shafts for ventilation. The size and number of the shafts was determined by the excavation rates and ventilation requirements not by the injection and withdrawal rates of the stored gas. These shafts were designed to be drilled and then lined with steel casing. Sinking the shafts represents a third of the construction cost for the project and they can be difficult to seal and cap after construction. Because of this, the location and size of the shafts was carefully calculated but final selection of the drilling method was left to the shaft contractor.

Construction of the caverns is scheduled to begin after the completion of the shafts with the mining of cross section tunnels that are 15 feet high by 18 feet wide. The main tunnels are then excavated from the cross section tunnels from the top down using controlled blasting techniques. During construction extensive use of rock bolts, mesh, and shotcrete is to be used to support slabs and rock wedges that might pose safety and integrity problems during construction and operation of the facility. Large inflows of water through fractures in the rock are to be high-pressure grouted to stem the flow of excessive water into the caverns with periodic pumping to remove the remainder.[37]

The cost of the facility was estimated to be $103.6 million in constant 1984 dollars. The time for construction was estimated at 52 months with the critical activity being the mining of the caverns.

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[37]Ibid., p. 206.

6.10.1.3. Proposal to Use the Caverns for Compressed Air Energy Storage.

In 1985 BUGC hired Fenix & Scisson to investigate the feasibility of using the mined caverns for gas peak-shaving storage during the four winter months and for compressed air energy storage (CAES) during the remaining months. Two purging cycles per year using sea or fresh water to remove gas or air from the caverns, were estimated at 14 days each. The company presented its findings at the Osaka Gas R & D Forum in 1985 and the study is the still the only one of its type that has been done in the U.S.

The study concluded that large metropolitan areas like New York with high peak-load demands during the summer because of air conditioning use, would benefit from the additional peak-load capacity of a CAES. The study concluded that a 50MW facility with an eight-hour generating/eight-hour charging time was feasible without increasing the existing size of the caverns. The additional cost of adding the CAES plant was estimated in 1984 constant dollars at $26.2 million ($5.1 million to modify the cavern and $20.5 million to build the plant). (see Appendix 6.12.)

6.10.1.4. Current Status of the Project

According to Michael B. Riordan an engineer consultant with the BUGC, the construction of a MNGSF or a combined MNGSF/CAES is "20 years or further out" in the future at BUGC given the current regulatory climate. However, the company is taking the precautionary measure of having the facility permitted including the costly and time consuming process of filing an environmental impact statement (EIS). The major concern that BUGC has is that its LNG plant, which operates on a yearly permit from the New York Fire Department, will not be renewed. There are significant concerns regarding the use and operations of LNG plants in densely populated areas.

However, the need for increased peak-shaving capacity by the year 2003 that initiated the 1982 feasibility study has changed significantly with the construction of several major pipelines that serve the New York metropolitan area. BUGC has secured twenty-year contracts with Canadian gas producers that have significantly increased the company's base load capacity during periods of high demand. Local distribution pipelines have also been. With these changes in the distribution and gas supply characteristics of the BUGC market, it is doubtful that a MNGSF will be built unless regulatory or environmental concerns force the closing of their LNG plant

6.11. Chapter 6 Conclusion

The projected increase in natural gas use by electric utilities, will increase the need for underground gas storage capacity in the US. The areas of the country that will be most effected by any shortage in storage capacity are the densely populated areas of the Northeast. They are heavily reliant on natural gas but are quite far from any naturally-occurring gas storage facilities. This has lead to an increased interests in manmade facilities for storing natural gas such as MNGSF, abandoned mines, and salt domes.

The prospect for extensive use of MNGSFs in the US faces significant obstacles although the idea has been extensively explored and the technology is well developed. The major obstacle is the cost of constructing a MNGSF compared with the cost of using depleted wells, solution mining salt domes or using abandoned mines. The other significant obstacle is that an unlined

MNGSF has never been built for peak-shaving use. This presents a certain element of risk and liability to the owner and contractor.

Any future market that might develop in engineering and constructing MNGSFs would certainly be attractive to the construction industry. The feasibility studies, design, and construction of these facilities are all construction related activities that any large construction commune with expertise in underground construction and mining could participate in.

Chapter 7: Thesis Conclusion

7.1 Conclusion

Construction activity has a direct and long-term effect on the environment. As private and public organizations search for methods to achieve more sustainable forms of development, the construction industry will be expected to contribute their expertise in planning, design, and construction to this effort. Research indicates that significant opportunities exist in the areas of hazardous waste; solid waste; energy; and waste-water treatment for construction firms with a proactive approach to developing new construction markets and to solving environmental problems. By applying new technologies, construction firms can mitigate the environmental impact of construction activity that is often necessitated by economic growth and increasing world populations.

7.2 Conclusion Regarding Opportunities for the Construction Industry in Reducing Airborne Emissions from the Production and Consumption of Energy

The construction industry can play a pivotal role in promoting technologies that mitigate the impact on the environment from the production and consumption of energy. As stated in the *Economist:*

> "Using energy in today's ways leads to more environmental damage than any other peaceful human activity (except perhaps reproduction). From deforestation to urban smog, from acid rain to airborne lead, from valleys flooded for hydroelectric schemes to rivers polluted with coal-mining waste, from Chernobyl to the

> *Exxon Valdez:* all are consequences of the production or consumption of energy. "[1]

The importance of the construction industry in alleviating these problems cannot be overstated. The construction industry will be expected to build new and more efficient power plants and to participate in finding new, alternative energy sources. It will be expected to apply new scrubber technologies that remove harmful pollutants from stack gasses before they enter the atmosphere. Additionally, the construction industry should actively participate in promoting energy-efficient technologies to reduce the current high level of energy consumed in residential, commercial, and industrial buildings. By applying standard, cost-effective technologies, energy consumption could be reduced between 30 and 70% in both new and existing buildings in the United States and other developed countries. This would effectively reduce airborne emissions from power plants by the same percentages. Additionally, many experts believe increasing the energy efficiency of buildings, represents the most cost-effective means of reducing airborne emissions and the environmental impact of producing and consuming all forms of energy.

The technologies analyzed in this thesis, are technologies that the construction industry could actively promote as partial solutions to the world's current environmental problems. Energy-efficient building designs and the different life-cycle costing methods need to be applied far more widely during the design process on new buildings. Ground source heat pumps; chill storage systems; phase changing materials for heat storage; and other energy efficient technologies will find far more widespread acceptance as the

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[1]"A power for good, a power for ill," A Survey of Energy and the Environment, *The Economist,* August 31, 1991.

environmental impact of buildings is considered more heavily by building construction professionals.

Construction firms that develop strategies today that account for changes to the industry caused by new environmental considerations will benefit in two ways. They will be able to participate in the preparation of new regulations and they will be able to respond quickly to opportunities in emerging environmental markets. New strategies must include measures for participating in research on new energy-efficient technologies; developing expertise internally on new technologies; and participating with product manufactures in trial installations of new technologies.

With more active participation by the construction industry, technologies such as chill storage and ground source heat pumps will develop far more rapidly than is currently possible. Construction firms that participate in early and ongoing research efforts will be well positioned when these technologies become widely accepted as standard systems for increasing the energy-efficiency of buildings.

7.3 Areas for Additional Research

Additional research in these technologies needs to be conducted in a variety of areas. These include:

- Research on market barriers to energy-efficient technologies and strategies to overcome them.
- Research on national policies and regulations that construction trade organizations could help change or promote to increase the use and affordability of energy-efficient technologies.
- Research on how to more effectively promote the development of energy-efficient technologies through collaborative efforts between product manufactures, contractors, government organizations, and universities.

- Research on methods for educating building design professionals, government organizations, and the public on the benefits to both commercial building owners and society of increased energy efficiency in buildings.

By conducting research in these areas, advocates of increased energy efficiency in buildings, both inside and outside the construction industry, could develop better methods for promoting important new technologies. Construction firms that actively participate in this pioneering research, will then have significant first entry advantages as these new energy-efficient technologies become more widely accepted.

Appendices

APPENDIX 2.1: WHICH METHODS TO USE FOR TYPICAL BUILDING DECISIONS

	Method					
Decisions	Life-Cycle Cost (LCC)[a]	Net Benefits(NB) and Net Savings (NS)	Benefit-to-Cost Ratio (BCR) and Savings-to Investment Ratio (SIR)	Internal Rate of Return (IRR)	Overall Rate of Return (OOR)	Discounted Payback (DPB) and Simple Payback (SPB)
Acceptance/rejection	•	Use	Use	◊	Use	◊
Design	•	Use	*	Don't Use	*	Don't Use
Size	•	Use	*	Don't Use	*	Don't Use
Combination	**,◊◊	◊◊	Use	Don't Use	Don't Use	Don't Use
Ranking	Don't use	Don't use	Use	Don't Use	Don't Use	Don't Use
Location	•	Use	*	Don't Use	*	Don't Use
Lease/Buy	•	Use	*	Don't Use	*	Don't Use
Replacement	•	Use	Don't Use	Don't Use	Don't Use	Don't Use

[a]Note that two or more LCC measures are required to make comparisons.

Symbols:

•=Use if costs predominate.

◊=Recommended only under limited circumstances, as described in the section.

*=Recommended only if incremental benefits and costs are used and each design/size is considered.

**= Recommended only if all projects are within a given building and facility.

◊◊=Recommended if overall life-cycle costs or aggregate net benefits for projects in combination are computed; not recommended if life-cycle costs or net benefits for individual projects are compared.

APPENDIX 2.2: DISCOUNT FORMULAS

Equation Name	Schematic Illustration	Application	Algebraic Form[A,B]
Single compound amount (SCA)	P ——▶ F?	to find F when P is known	$F = P\left[(1+i)^n\right]$
Single present value (SPW)	P? ◀—— F	to find P when F is known	$P = F\left(\frac{1}{(1+i)N}\right)$
Uniform sinking fund (USF)	A? + A? ··· + A? ◀— F	to find A when F is known	$A = F\left(\frac{i}{(1+i)^N - 1}\right)$
Uniform capital recovery (UCR)	P —▶ A? + A? ··· + A?	to find A when P is known	$A = P\left(\frac{i(1+i)^N}{(1+i)^N - 1}\right)$
Uniform compound amount (UCA)	A + A ··· + A —▶ F?	to find F when A is known	$F = A\left(\frac{(1+i)^N - 1}{i}\right)$
Uniform present value (UPW)	P? ◀— A + A ··· + A	to find P when A is known	$P = A\left(\frac{(1+i)^N - 1}{i(1+i)^N}\right)$
Modified uniform present value (UPW*)[C]	P? ◀— A_1 + A_2 ··· + A_n	to find P when known A_O is escalating at rate e.	$P = A_0\left(\frac{1+e}{1-e}\right)\left[1-\left(\frac{1+e}{1+i}\right)^N\right]$

P = present sum of money,
F = future sum of money equivalent to P at the end of N periods of time at i interest or discount rate,
A = end-of-period payment (or receipt) in a uniform series of payments (or receipts) over N periods at i interest or discount rate,
A_O = initial value of a periodic payment (receipt) evaluated at the beginning of the study period,
$A_n = A_O \cdot (1+e)^t$, where $t=1,\cdots,N$,
N= number of interest or discount periods,
i= interest or discount rate, and
e= price escalation rate per period.

APPENDIX 2.2 (Cont.): DISCOUNT RATES

[A] Note that the USF, UCR, UCA and UPW equations yield undefined answers when i=0. The correct algebraic forms for this special case would be as follows: USF formula, $A=F/N$; UCR formula, $A=P/N$; UCA formulas, $F=A \cdot N$. The UPW* equation also yields an undefined answer when $e=i$. In this case, $P=A_o \cdot N$.

[B] The terms by which the known values are multiplied in these equations are the formulas for the factors found in discount factor tables. Using acronyms to represent the factor formulas, the discounting equations can also be written as $F=P \cdot SCA$, $P=F \cdot SPW$, $A=F \cdot USF$, $A=P \cdot UCR$, $F=A \cdot UCA$, $P=A \cdot UPW$, and $P=A_o \cdot UPW^*$.

[C] To find P when A_t changes from year to year at a different rate each year (either due to a change in physical quantity, or both), use the following equation:

$$P = \sum_{t=1}^{N} \frac{A_t}{(1+i)^t}$$

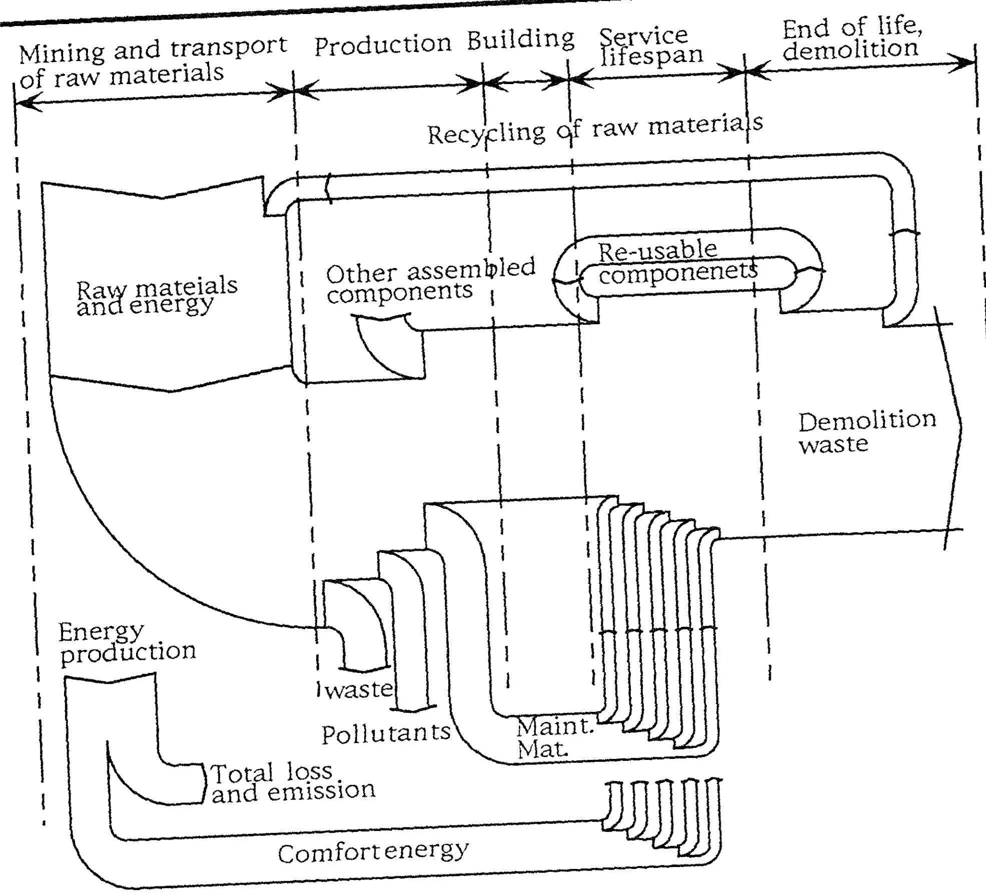
Where:

$A_t = A_{t-1} \cdot (1+e_t)$, and

t= the rate of change in A for year t.

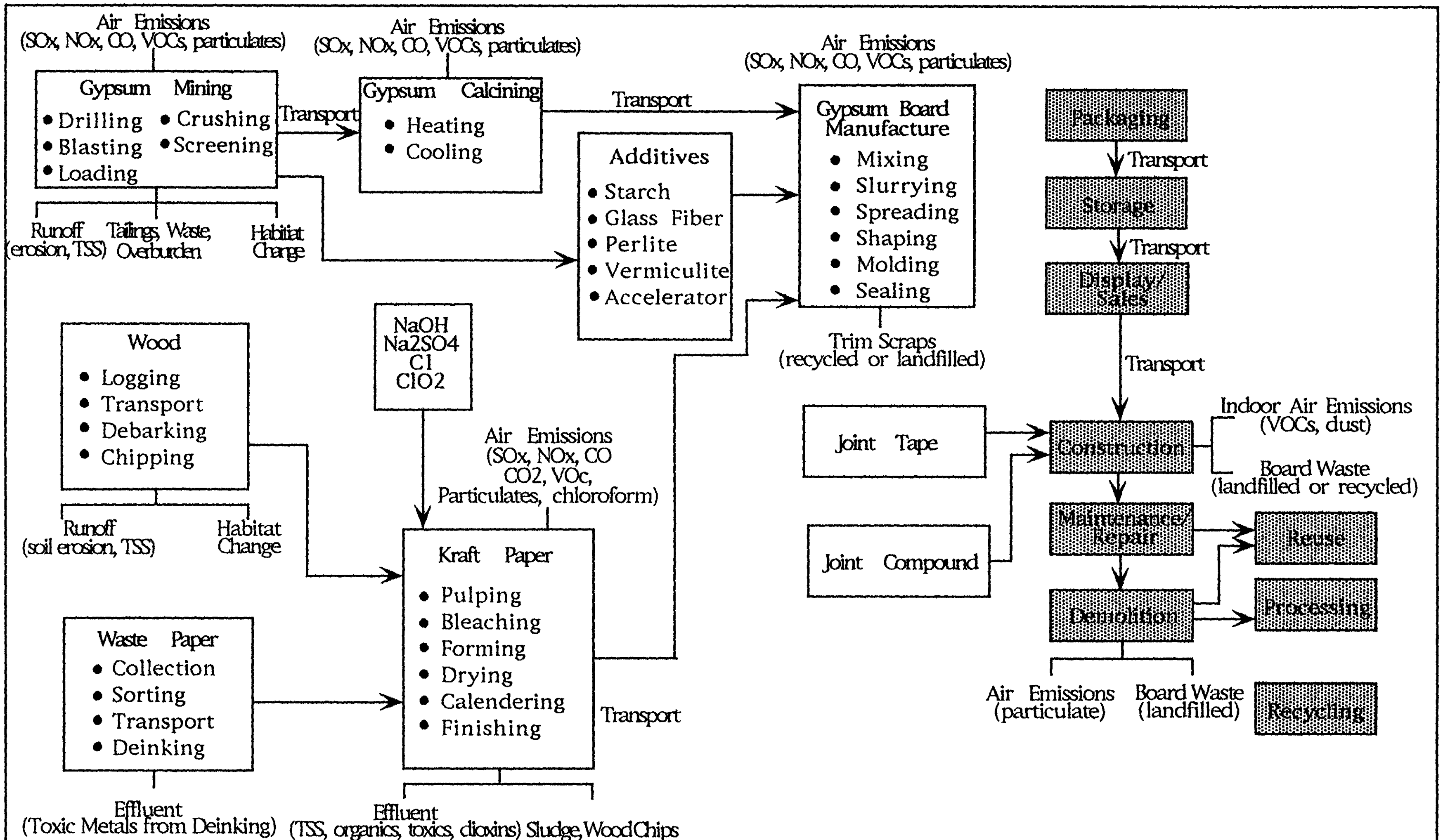
Source:American Society for Testing and Materials (ASTM), *Standard Practice for Measuring Life_Cycle Costs of Building Systems.* E917-89. p. 771.

APPENDIX 2.3: LIFE-CYCLE FLOW DIAGRAM



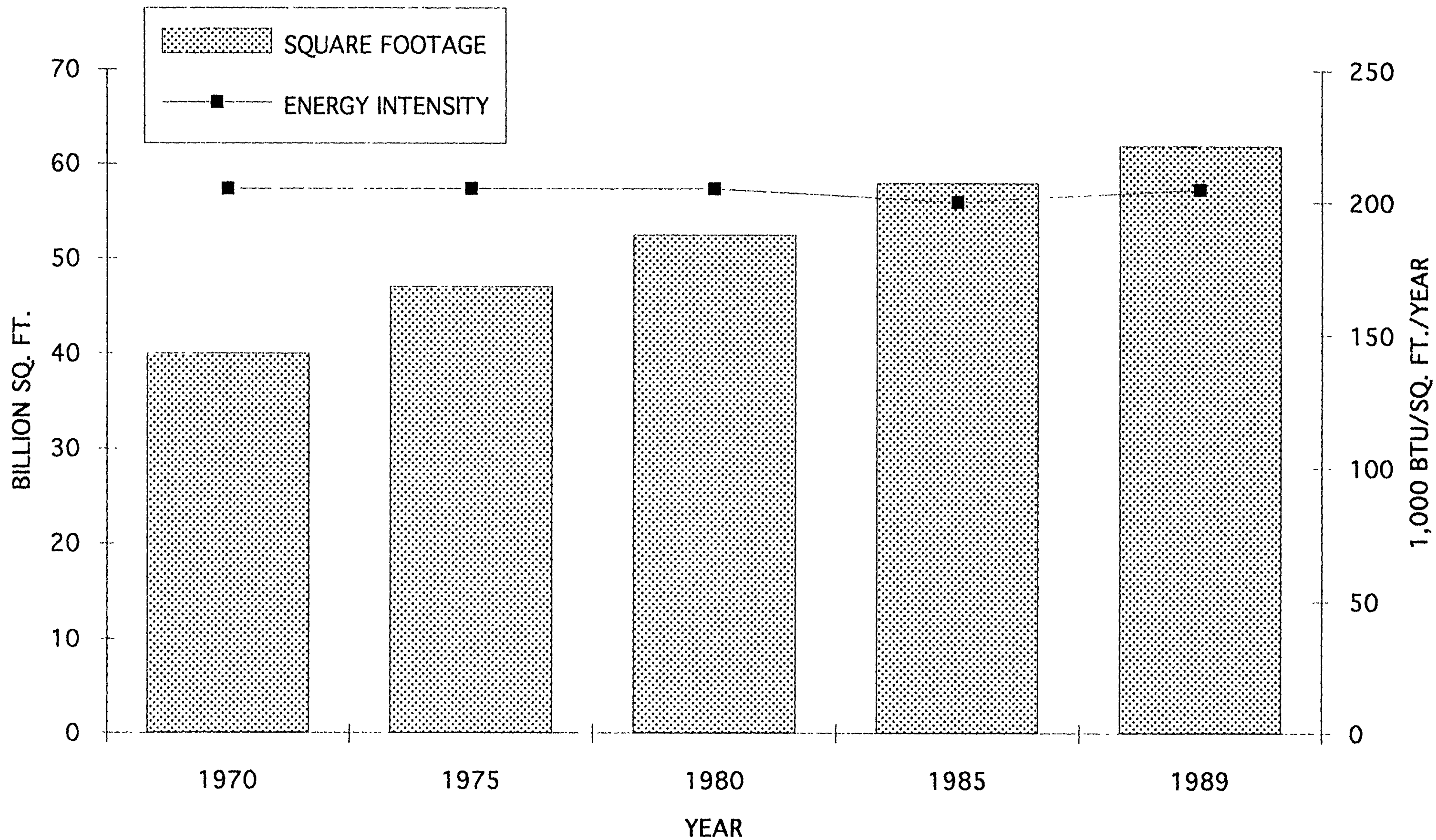
Source:P.C.F. Bekker, *A Life-cycle Approach in Building*, Building and Environment, Vol. 17, pp. 55-61, 1982.

APPENDIX 2:4 : LIFECYCLE SUMMARY OF GYPSUM WALLBOARD



Source: AIA Environmental Resource Guide Subscription, July 1993

APPENDIX 2.5: SQUARE FOOTAGE AND ENERGY INTENSITY OF COMMERCIAL BUILDINGS IN THE US



APPENDIX 2.6: ENERGY EFFICIENCY ISSUES

HVAC

- Peak load sizing with optimization for part-load performance
- Chiller efficiency-compressor, motor, multiple staging, condenser efficiency, chilled water temperature optimization
- Pumping systems-staging, system losses, variable-speed pumping
- Air/water-side economizer systems
- Supply air temperature assesment-low-temperature systems
- High-efficiency boilers
- High -efficiency motor selection
- Electronic motor speed controls
- Heat-recovery options

PLUMBING

Water heating options
Pump sizing/low-load systems
Heat-recovery opportunities

END-USE EQUIPMENT

Kitchen equipment efficiency-refrigeration, fryers, griddles, ovens, cooktops, broilers, heat recovery
Office equipment-computers, copying systems, communication equipment

CONTROLS

- architecture Direct digital control
- systems
- Internal HVAC equipment intelligence
- Tenant amenities opportunities
- Energy-use reporting/trend-logs
- Information/control compatibility between system components

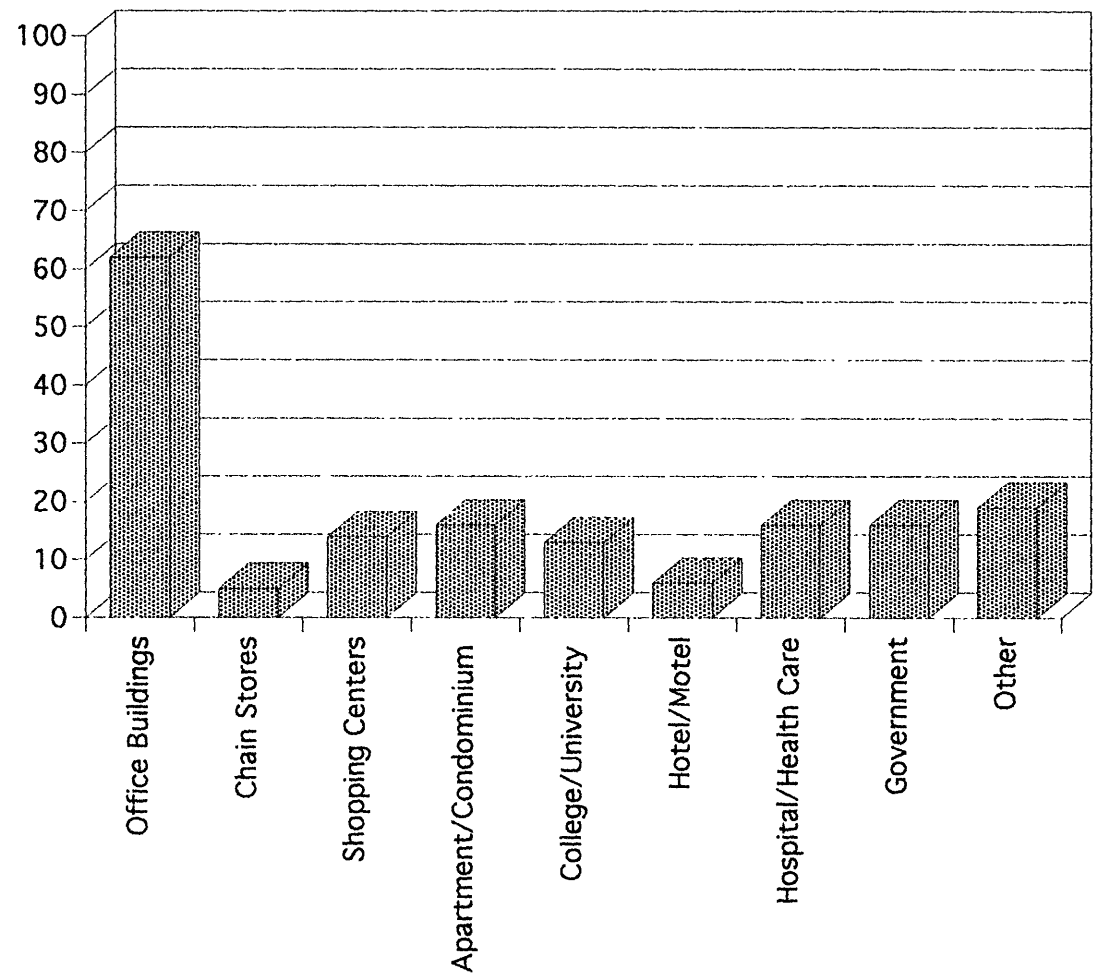
LIGHTING

- Optimization of layout with interiors design
- Fixture/lamp selection
- Ballast options
- Daylighting design
- Illumination levels matched to visual tasks/ability to tune output
- Lighting controls-occupancy sensors, multi-level switching, time-of-day controls

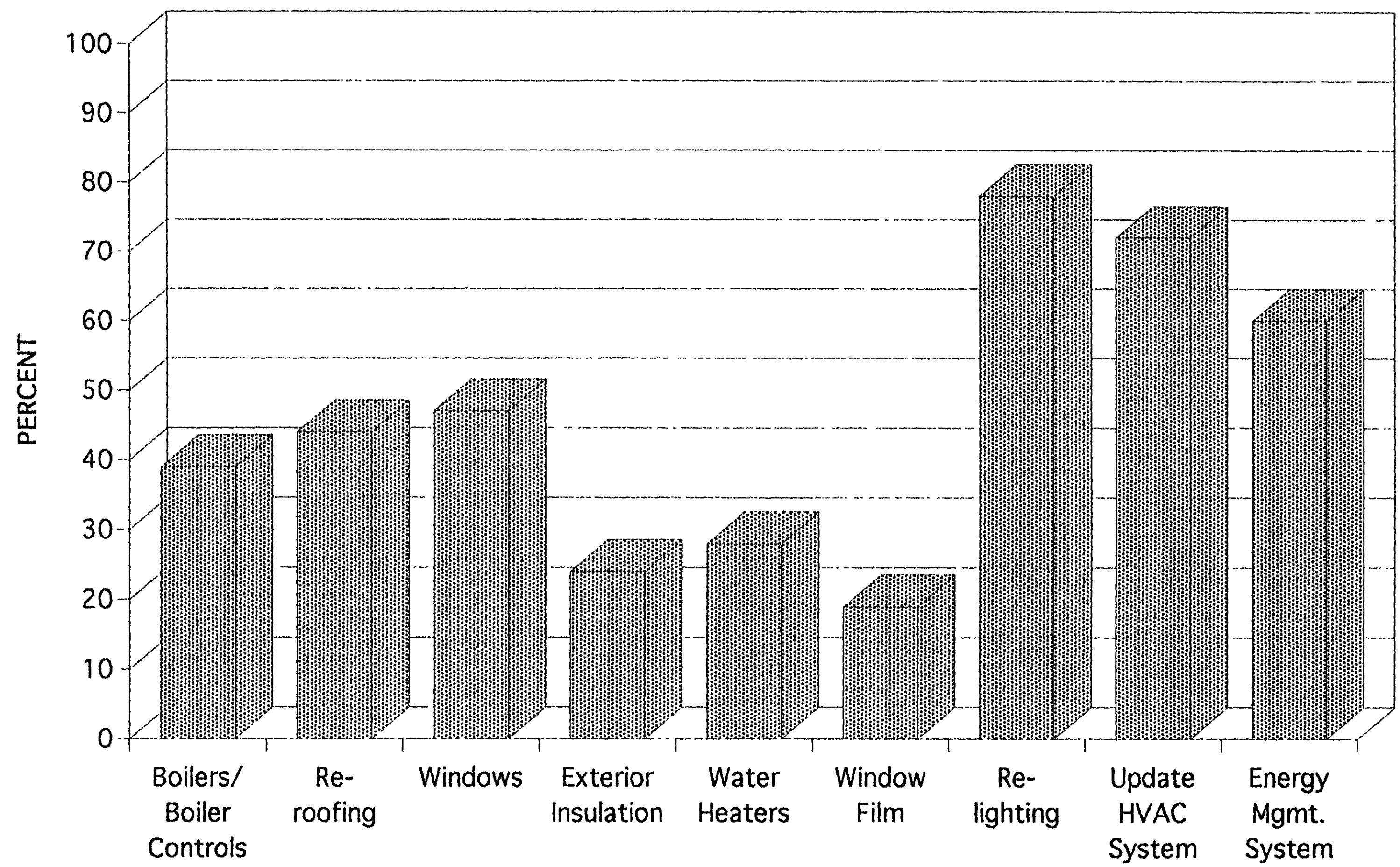
ENVELOPE

- Selective glazing material
- Optimization of glazing area, type and U-value by facades
- Daylighting integration-glazing modifications and light controls
- Insulation analysis
- Skylight atrium analysis

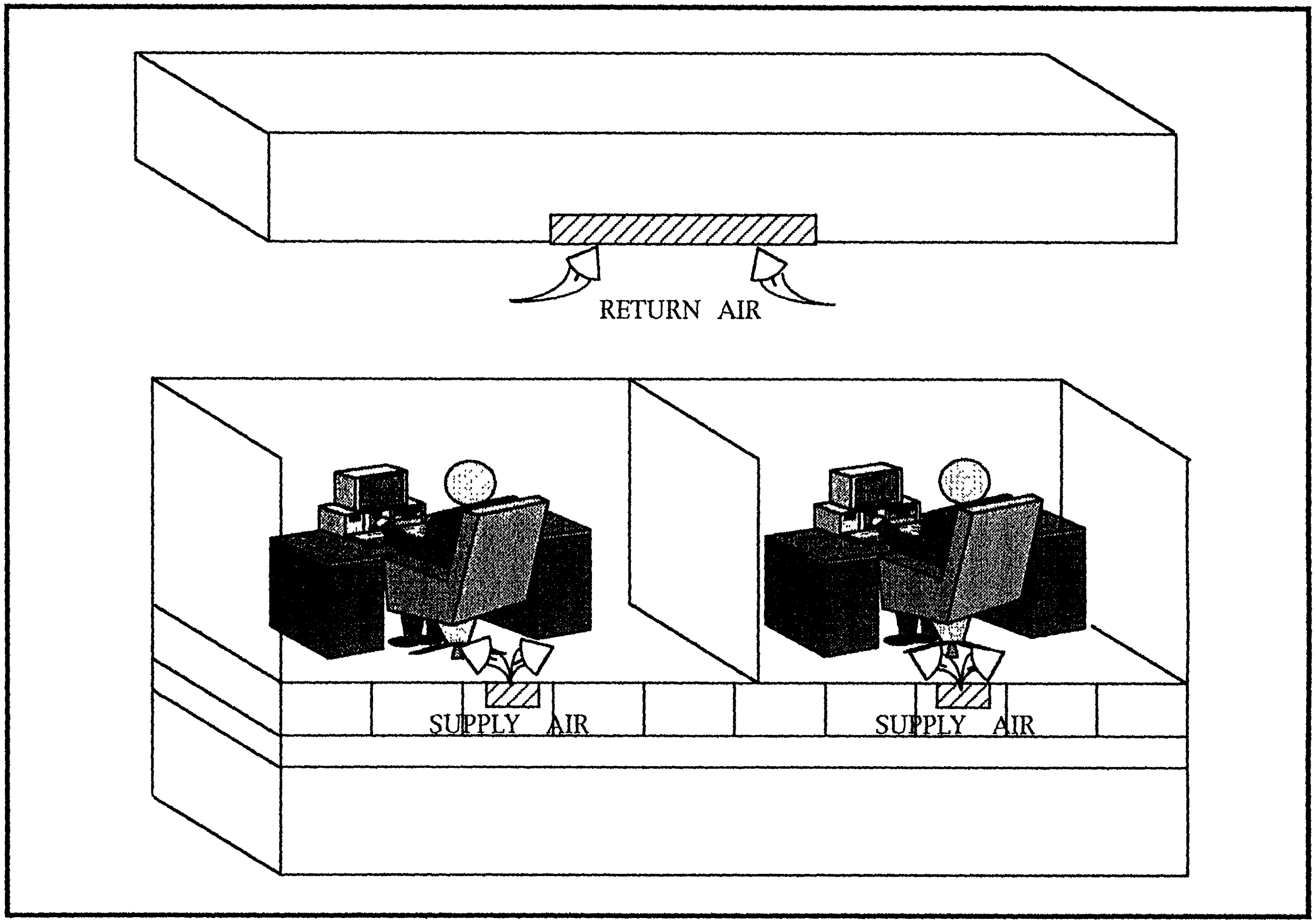
APPENDIX 2:7: TYPES OF BUILDINGS TO BE MODERNIZED IN 1993



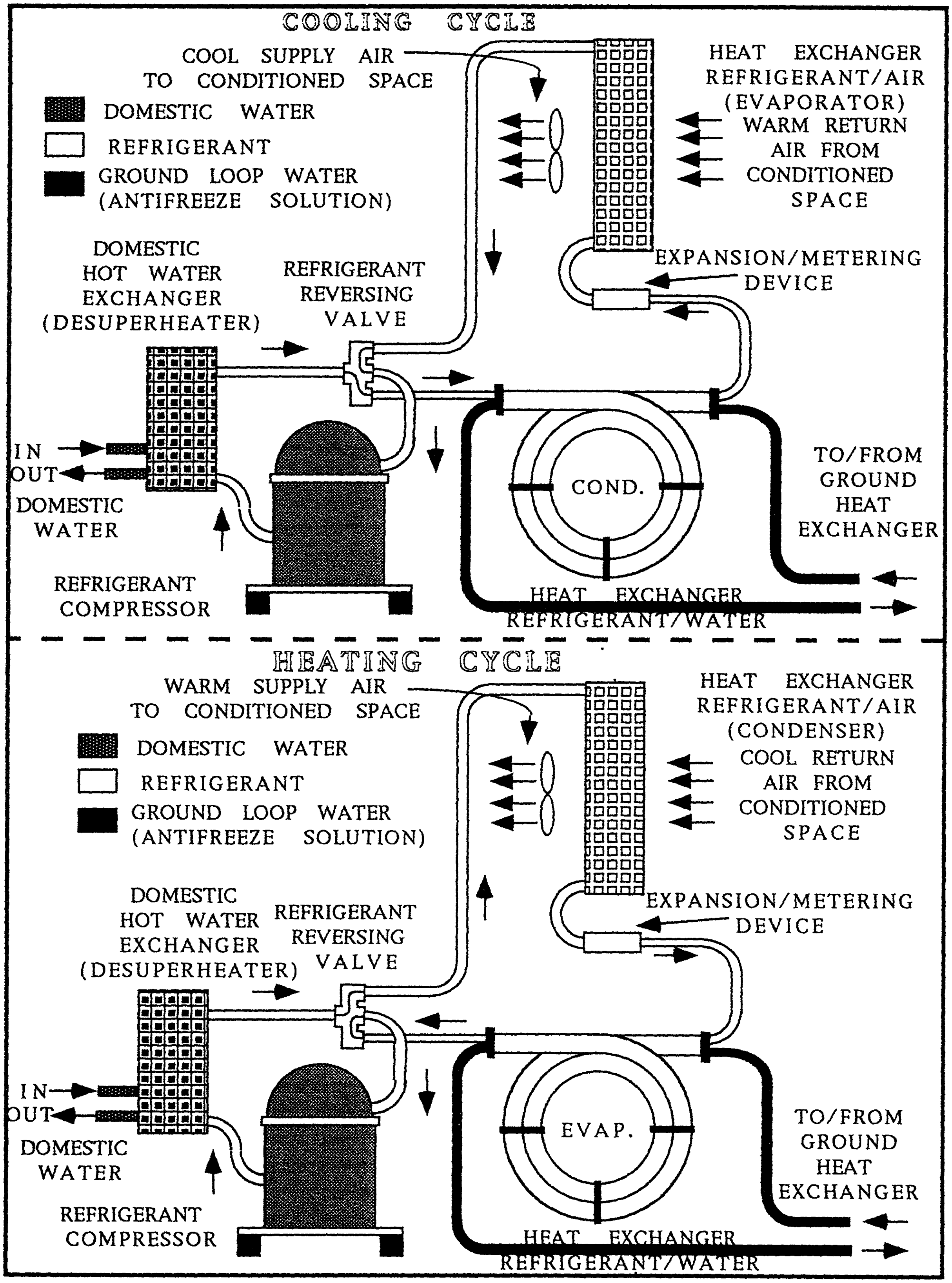
APPENDIX 2.8: TYPES OF SYSTEMS TO BE ADDED FOR INCREASED ENERGY EFFICIENCY



APPENDIX 2.9: PERSONAL ENVIRONMENT MANAGER

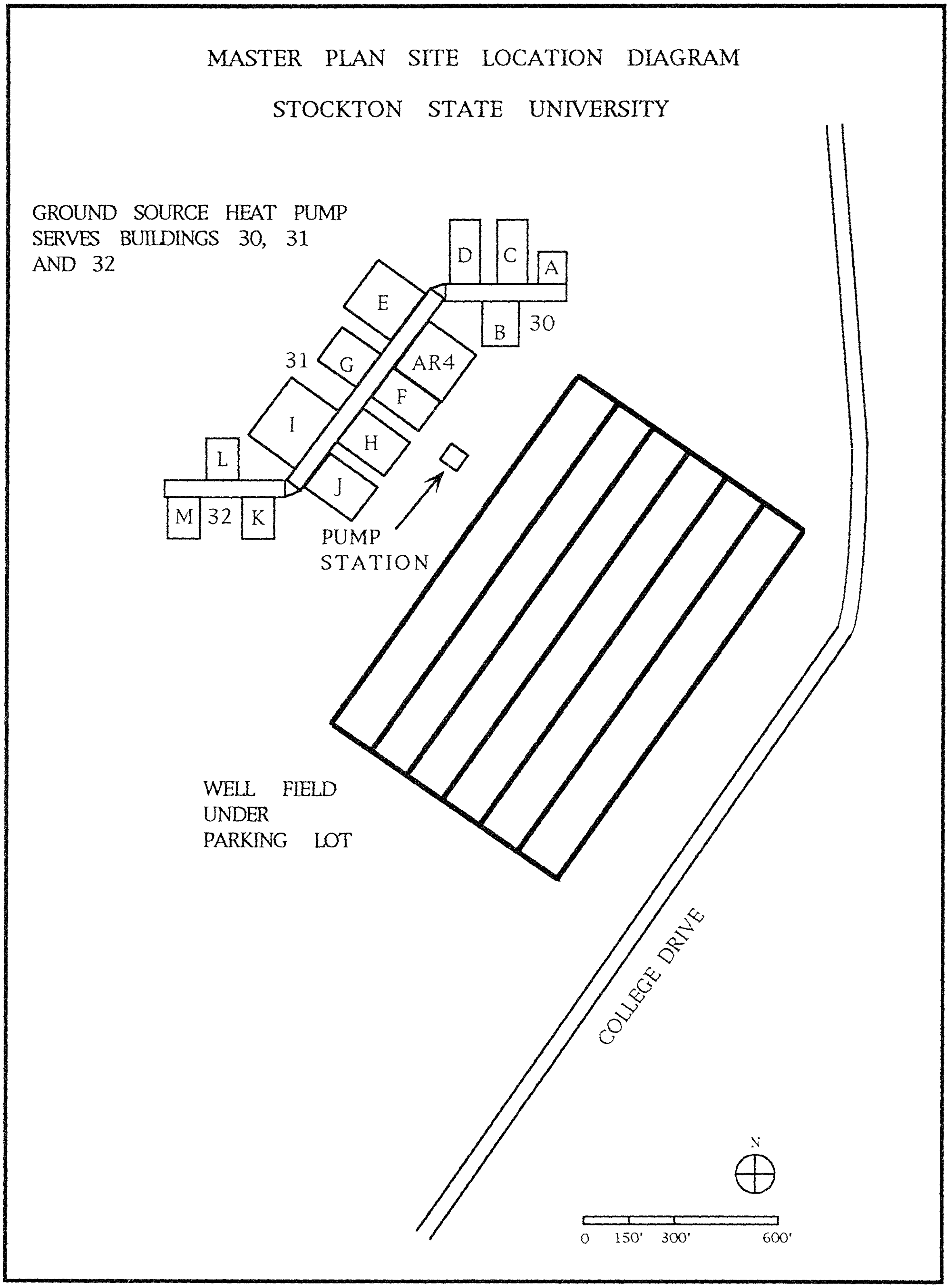


APPENDIX 3.1: GSHP HEATING AND COOLING CYCLES

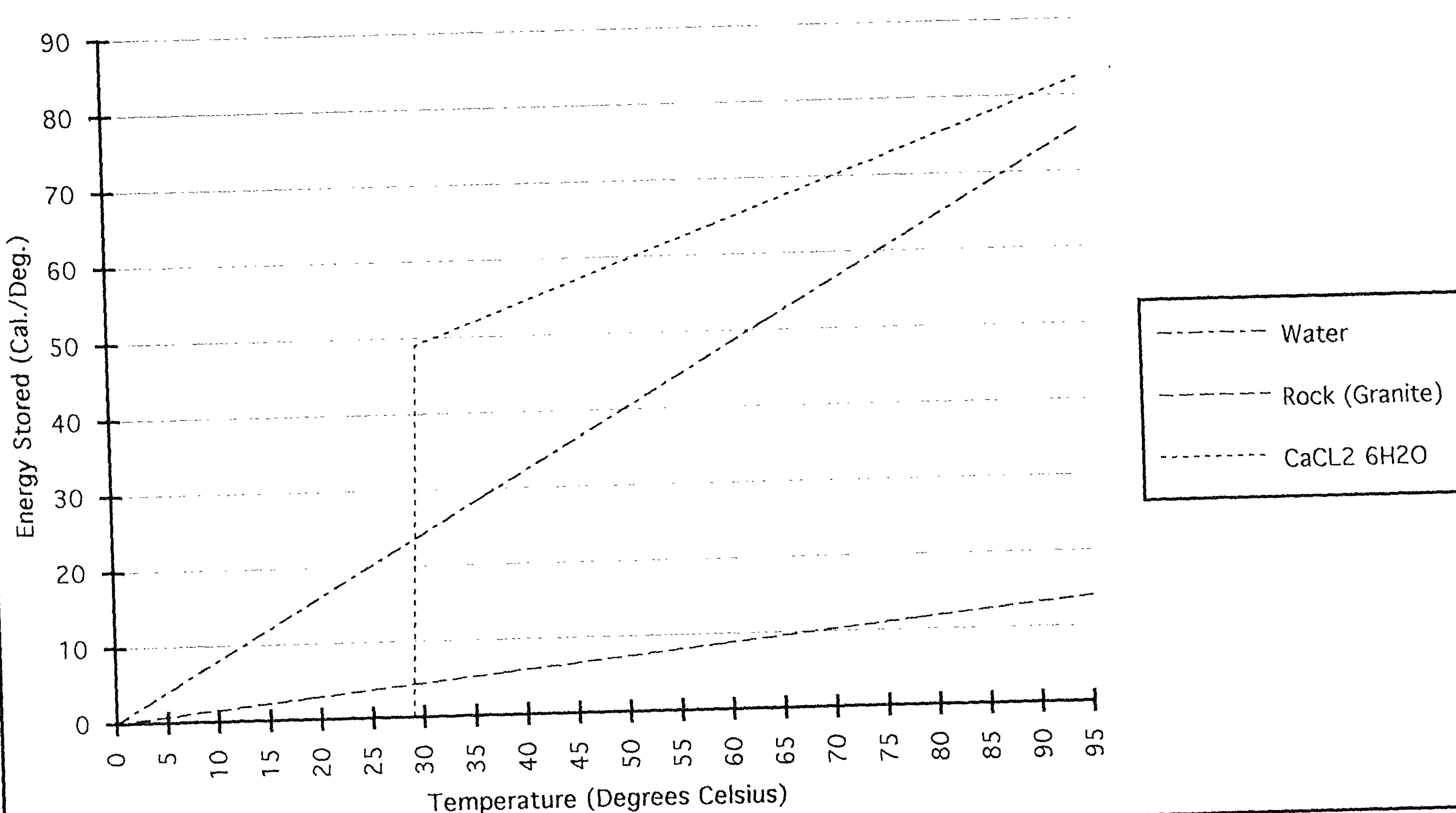


Source: Closed-loop Ground Source Heat Pump Systems, Installation Guide, NRECA Project 86-1 Oklahoma State University

APPENDIX 3.2.


MASTER PLAN SITE LOCATION DIAGRAM
STOCKTON STATE UNIVERSITY
GROUND SOURCE HEAT PUMP
SERVES BUILDINGS 30, 31
AND 32
D
C
A
E
B
30
31
G
AR4
F
I
H
L
J
M
32
K
PUMP
STATION
WELL FIELD
UNDER
PARKING LOT
COLLEGE DRIVE
N
0
150'
300'
600'

APPENDIX 4.1: COMPARISON OF HEAT STORAGE CAPACITY OF PCM AND SENSIBLE STORAGE MEDIA FOR 20 DEGREE CELSIUS AIR HEATING SYSTEM



APPENDIX 5.1: RATE SCHEDULE FOR SOUTHERN CALIFORNIA EDISON

		DEMAND CHARGE ($/kWh)*						ENERGY CHARGE (cents/kWh)**					
		SUMMER			WINTER			SUMMER			WINTER		
RATE OPTION	ALL YEAR	ON PEAK	MID PEAK	OFF PEAK	ON PEAK	MID PEAK	OFF PEAK	ON PEAK	MID PEAK	OFF PEAK	ON PEAK	MID PEAK	OFF PEAK
CURRENT													
GENERAL SERVICE	1.000							18.211		6.064	16.774		6.253
TOU-8		3.000	0.850	0.500	3.000	0.850	0.500	13.822	7.160	5.918	11.637	7.351	6.021
TOU-SOP (LARGE)		8.000	2.000	0.500	3.500	2.000	0.500	20.959	6.020	3.001	12.275	6.020	3.001
GS-2	3.800							7.690	7.690	7.690	7.690	7.690	7.690
PROPOSED													
TOU-8		7.000	2.000	0.500	2.000	2.000	0.500	14.220	6.969	3.112*	12.585	8.263	3.112*
TOU-8-SOP		8.500	4.000	0.000	2.000	2.000	0.000	22.336	6.329	2.512**	15.415	6.329	2.512**
TOU-GS-SOP		8.500	4.000	0.000	2.000	2.000	0.000	22.155	6.626	2.712[3]	19.608	6.626	2.712[3]
GS-2													
>1st 500 kWh	6.000							7.571	7.571	7.571	7.571	7.571	7.571
>ADDITIONAL (kWh)								3.512	3.512	3.512	3.512	3.512	3.512

1. Rate schedule does not include monthly customer charge and meter fees.

*First 275 kWh per on-peak kW, of off-peak kWh, per kWh is 6.329.

** First 100 kWh per on-peak kW, of off-peakm kWh is 5.767 cents in the summer, 5.463 cents in the winter.

3. First 100 kWh per on-peak kW of off-peak kWh, per kWh is 6.025 cents in summer and 5.714 in the winter.

4. Summer is June through September.

APPENDIX 5.2: ELECTRIC UTILITY THERMAL STORAGE FINANCIAL INCENTIVE PROGRAMS (JULY, 1987)

UTILITY	INDUCEMENT PER KW OF LOAD SHIFT				MAXIMUM PER PROJECT
ARIZONA PUBLIC SERVICE COMPANY	$250 FOR FIRST 200 KW PLUS				NONE
	$115 FOR ALL KW OVER 500				
BOSTON EDISON	$200				NONE
CITY OF AUSTIN, TX POWER & LIGHT	VARIABLE - THREE YEAR PAYBACK UP				NONE
	TO $300 PER KW				
CITY OF PALO ALTO, CA	$400 NEW CONSTRUCTION				$250,000
	$550 RETROFIT				
EL PASO ELECTRIC CO.	$200 OR ACCEPTABLE PAYBACK				NONE
LONG ISLAND LIGHTING CO.	$300				$50,000
					40% OF COST OR
					$150,000 PER
LOS ANGELES DEPT. OF WATER & POWER	$250				BUILDING
OKLAHOMA GAS & ELECTRIC CO.	$200				$50,000
	F.S. = $500 - $1500				
PACIFIC GAS & ELECTRIC CO.	$200				$150,000
PUBLIC SERVICE OF NJ	$250 FOR FIRST 500 KW PLUS				NONE
	$125 FOR ALL KW OVER 500				
SACRAMENTO MUNICIPAL UTILITY DISTRICT	$250				NONE
	F.S. = LIMITED NUMBER				
SALT RIVER PROJECT	$250 FOR FIRST 300 KW PLUS				500KW-$98,000
	$115 FOR NEXT 200 KW				
SAN DIEGO GAS & ELECTRIC CO	RATE	0-200KW	201-1200KW	1200KW	$300,000
	TOU	$250	$225	$200	
	FLAT	$350	$325	N/A	
		0-200 TON	201-1200 TON	1200 TON	
NEW CONSTRUCTION	BOTH	$350 PER TON	$225 PER TON	$200 PER TON	
SOUTHERN CALIFORNIA EDISON	$200/KW				$300,000
	F.S = $$5000 MAXIMUM				

APPENDIX 5.2 (cnt): ELECTRIC UTILITY THERMAL STORAGE FINANCIAL INCENTIVE PROGRAMS (JULY, 1987)

UTILITY	INDUCEMENT PER KW OF LOAD SHIFT	MAXIMUM PER PROJECT
TEXAS ELECTRIC UTILITIES COMPANY	$350 FOR FIRST 200 KW PLUS $250 FOR NEXT 300 KW PLUS $200 FOR NEXT 500 KW PLUS $125 FOR ALL KW OVER 1000	NONE
WISCONSON ELECTRC POWER COMPANY	$200 OR 5 YEAR NO INTEREST LOANS UP TO $750 PER KW F.S. - MATCH TO $5000	NONE

KEY: F.S. = FEASIBILITY STUDY

SOURCE: INTERNATIONAL THERMAL STORAGE ADVISORY COUNCIL (JULY, 1987) NEWSLETTER.

APPENDIX 3: PER PARTICIPANT DEMAND AND ENERGY IMPACTS FOR DSM PROGRAMS

PROGRAM/TECHNOLOGY TYPE	DEMAND IMPACTS [1] RANGE (KW)	DEMAND IMPACTS [1] AVERAGE (KW)	ENERGY IMPACTS [1] RANGE (MWH/YR)	ENERGY IMPACTS [1] AVERAGE (MWH/YR)
AUDIT BUILDING ENVELOPE				
SUMMER--IMPACT RESIDENTIAL				
HIGH-COST WEATHERIZATION	0.90 TO 1.43	0.59		
LOW-COST WEATHERIZATION	0.01 TO 0.60	0.12		
BUILDING STANDARD	0.11 TO 4.00	1.24		
WINTER IMPACT --RESIDENTIAL				
HIGH-COST WEATHERIZATION	0.12 TO 1.26	0.61		
LOW-COST WEATHERIZATION	0.01 TO 1.00	0.08		
BUILDING STANDARD	0.07 TO 5.50	1.88		
ANNUAL IMPACT--RESIDENTIAL				
HIGH-COST WEATHERIZATION			0.43 TO 7.38	2.15
LOW-COST WEATHERIZATION			0.04 TO 1.17	0.38
BUILDING STANDARD			0.28 TO 9.96	2.86
ANNUAL--NON-RESIDENTIAL				
AUDIT SERVICES			0.10 TO 476.20	62.30
HIGH-COST WEATHERIZATION			156.90 TO 356.50	233.60
HVAC EQUIPMENT				
SUMMER IMPACT				
RESIDENTIAL AC			0.06 TO 0.71	0.48
RESIDENTIAL AC/AIR SOURCE	0.15 1.72	0.83		
RESIDENTIAL AC/ROOM HP	0.09 0.46	0.23		
RESIDENTIAL AC/HP TUNE UP	0.07 1.66	0.62		
RESIDENTIAL GEOTHERMAL HP	0.33 2.00	1.20		
NON-RESIDENTIAL AC			1.07 TO 24.80	10.88
NON-RESIDENTIAL HP/AC	0.50 TO 44.86	12.57		
NON-RESIDENTIAL CHILLERS	0.53 TO 34.28	11.48		

APPENDIX 3 (cont.): PER PARTICIPANT DEMAND AND ENERGY IMPACTS FOR DSM PROGRAMS					
	DEMAND IMPACTS [1]			ENERGY IMPACTS [1]	
PROGRAM/TECHNOLOGY TYPE	RANGE (KW)		AVERAGE (KW)	RANGE (MWH/YR)	AVERAGE (MWH/YR)
WINTER IMPACT					
RESIDENTIAL AIR SOURCE HP	1.40 TO	5.20	2.74		
	2.00 TO	8.70[2]	4.30[2]		
RESIDENTIAL GEOTHERMAL HP	1.60 TO	8.40	4.65		
RESIDENTIAL ADD-ON HP	4.50 TO	15.00	8.20		
RESIDENTIAL DUAL-FUEL HEATING	7.00 TO	21.00[2]	16.25[2]		
ANNUAL IMPACT					
RESIDENTIAL AIR-SOURCE HP	0.57 TO	5.20	2.30		
	0.80 TO	6.80[2]	4.80[2]		
RESIDENTIAL GEOTHERMAL HP	5.20 TO	11.25[2]	7.24[2]		
RESIDENTIAL ADD-ON HP	1.06 TO	5.10[2]	2.68[2]		
LGHTING EQIPMENT					
INTERIOR APPLICATIONS					
RESIDENTIAL	0.01 TO	0.22	0.04	0.05 TO 0.51	0.17
NON-RESIDENTIAL	0.15 TO	219.00	21.00	1.20 TO 1086.00	113.00
EXTERIOR APPLICATIONS	0.10 TO	1.30[2]	0.67[2]	0.04 TO 13.80[2]	2.87[2]
EFFICIENT EQUIPMENT					
WATER HEATERS					
RESISTANCE	0.01 TO	0.50	0.18	0.29 TO 0.48	0.39
	0.25 TO	4.00	2.04	0.35 TO 6.10	4.40
STORAGE	0.01 TO	1.00	0.70		
	1.00 TO	3.60	2.30		
HEAT RECOVERY	0.15 TO	1.80	0.79	0.18 TO 8.70	4.82
HEAT PUMP	0.15 TO	0.20	0.18	1.36 TO 2.23	1.79
SOLAR	0.20 TO	0.57	0.38	0.90 TO 2.70	2.43
REFRIGERATORS/FREEZERS					
INSTALLATION	0.01 TO	0.08	0.03	0.13 TO 0.19	0.16
REMOVAL	0.05 TO	0.32	0.16	0.51 TO 1.70	1.08

APPENDIX 3 (Cont.): PER PARTICIPANT DEMAND AND ENERGY IMPACTS FOR DSM PROGRAMS

	DEMAND IMPACTS [1]		ENERGY IMPACTS [1]	
PROGRAM/TECHNOLOGY TYPE	RANGE (KW)	AVERAGE (KW)	RANGE (MWH/YR)	AVERAGE (MWH/YR)
TIMERS	0.01 TO 0.06	0.04	0.31 TO 0.45	0.37
AGRICULTURAL EQUIPMENT				
IRRIGATION SYSTEM	1.64 TO 76.30	21.40	8.20 TO 24.70	16.50
VENTILLATORS	0.60 TO 0.67	0.64	1.00 TO 1.67	1.34
THERMAL STORAGE				
HEAT STORAGE	0.40 TO 200.00	21.60		
COOL STORAGE	100.00 TO 1125.00	411.90		
LOAD CONTROL				
WATERHEATERS				
SUMMER	0.14 TO 1.10	0.60		
WINTER	0.14 TO 2.00	0.94		
AIR CONDITIONERS				
RESIDENTAL	0.17 TO 2.55	0.98		
COMMERCIAL	1.65 TO 18.80	6.32		
SPACE HEATERS	0.50 TO 2.20	1.10		
POOL PUMPS	0.40 TO 1.30	0.78		
IRRIGATION PUMPS	5.70 TO 233.00	34.68		
SPECIAL RATES				
INTERRUPTIBLE	68.00 TO 16800.00	1180.00		
TIME-OF-USE				
RESIDENTIAL	0.28 TO 1.50	0.90		
NON-RESIDENTIAL	10.00 TO 10000.00	83.00		
ECONOMIC DEVELOPMENT	367.00 TO 6900.00	1900.00		
REAL-TIME	80.00 TO 197.92	182.00		
COINCIDENT DEMAND	22.70 TO 250.00	57.90		

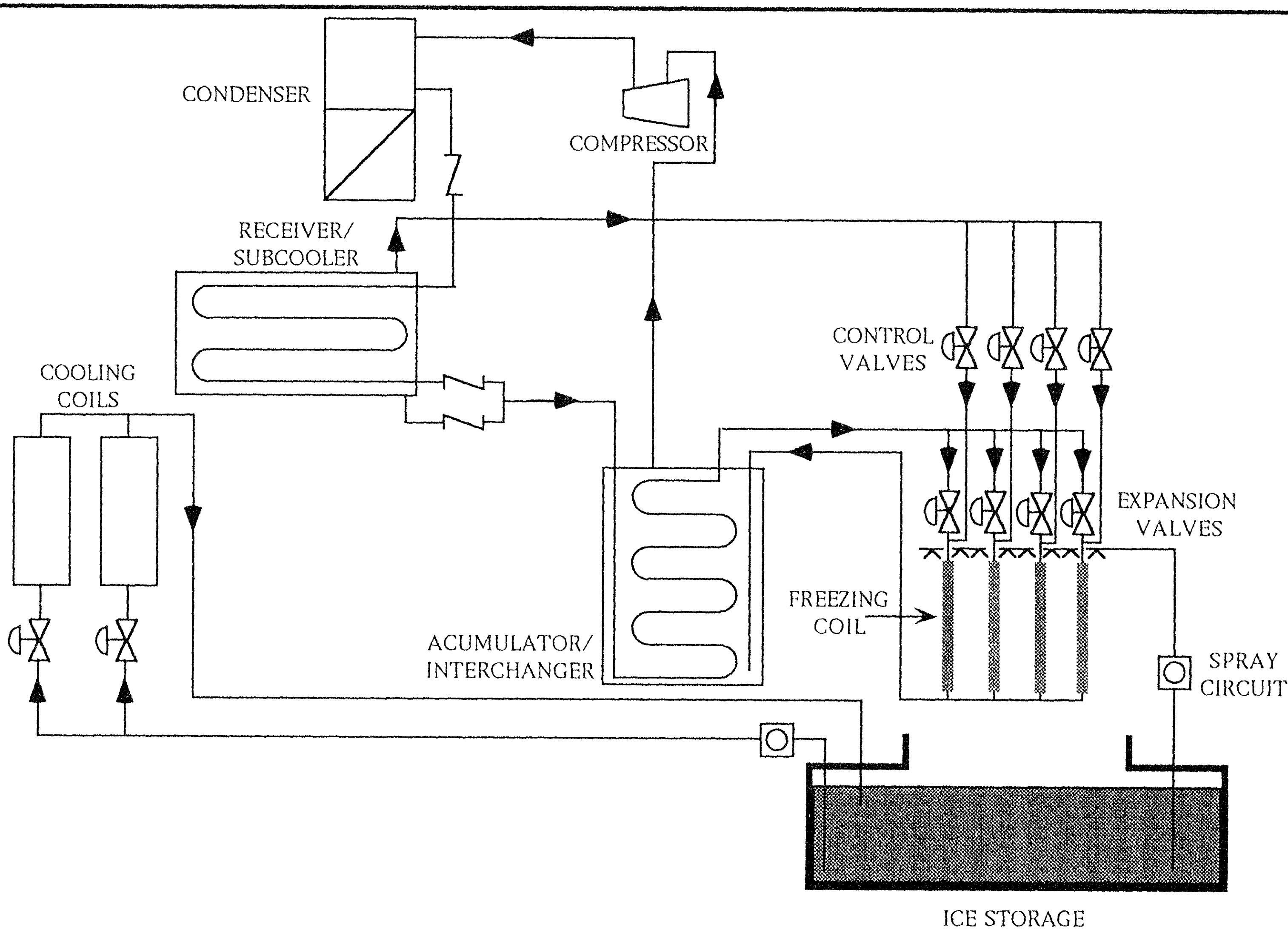
APPENDIX 3 (Cont.): PER PARTICIPANT DEMAND AND ENERGY IMPACTS FOR DSM PROGRAMS

PROGRAM/TECHNOLOGY TYPE	DEMAND IMPACTS [1] RANGE (KW)	DEMAND IMPACTS [1] AVERAGE (KW)	ENERGY IMPACTS [1] RANGE (MWH/YR)	ENERGY IMPACTS [1] AVERAGE (MWH/YR)
MOTORS AND DRIVES	0.40 TO 50.00	7.60		
STANDBY GENERATION	125.00 TO 10000.00	670.00		

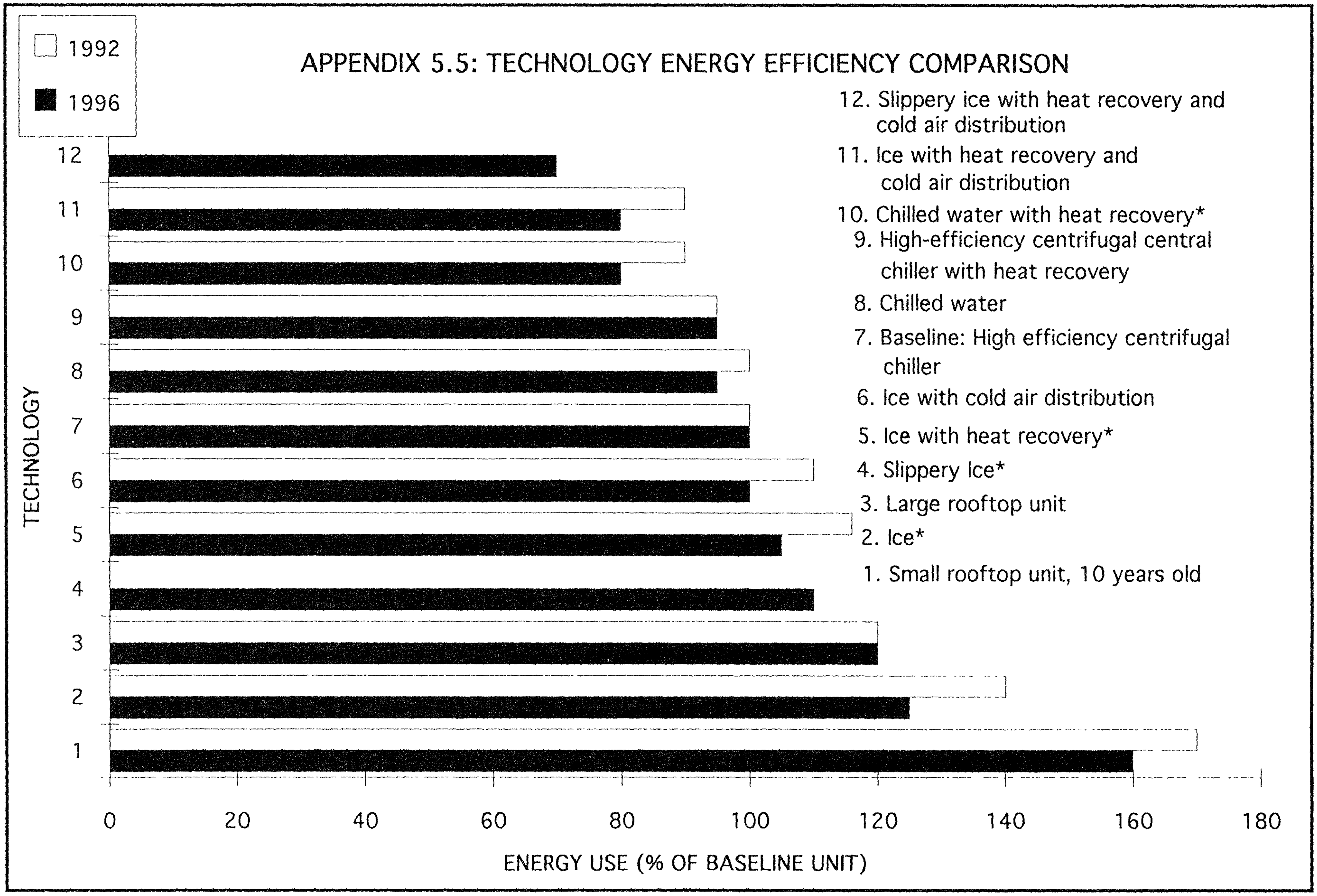
1 ENTRIES REFER TO REDUCTIONS UNLESS OTHERWISE INDICATED
2 REFERS TO LOAD ADDITION OR SALES INCREASE

DEMAND IMPACTS: Reduction of peak energy demand
ENERGY IMPACTS: Annual energy savings
SOURCE: 1992 SURVEY OF UTILITY DSM PROGRAMS, EPRI, TR-102193, TABLE S-9

APPENDIX 5.4: SPRAYED FREEZING COIL ICE-MAKER UNIT

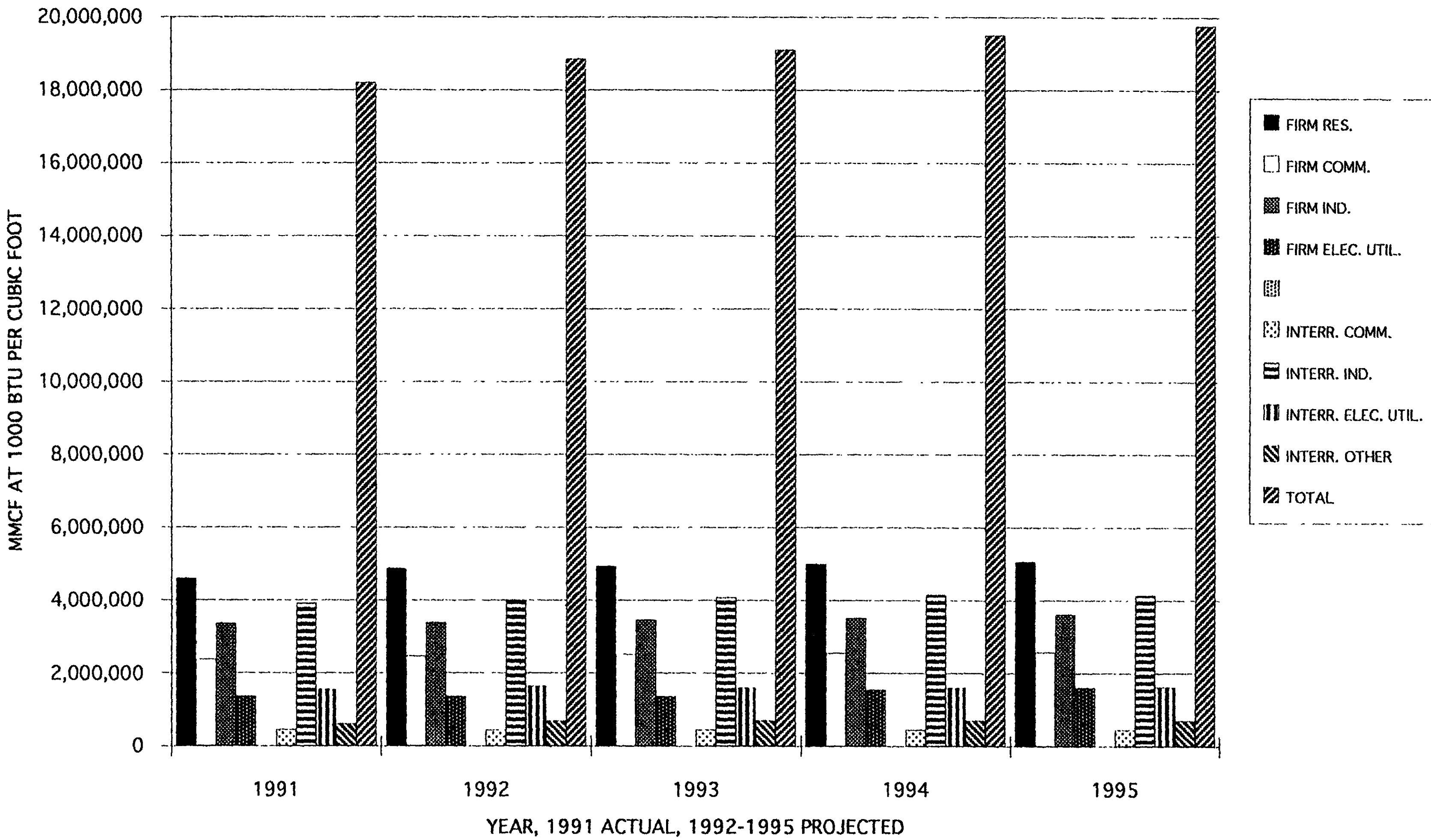


SOURCE: COMMERCIAL COOL STORAGE GUIDE

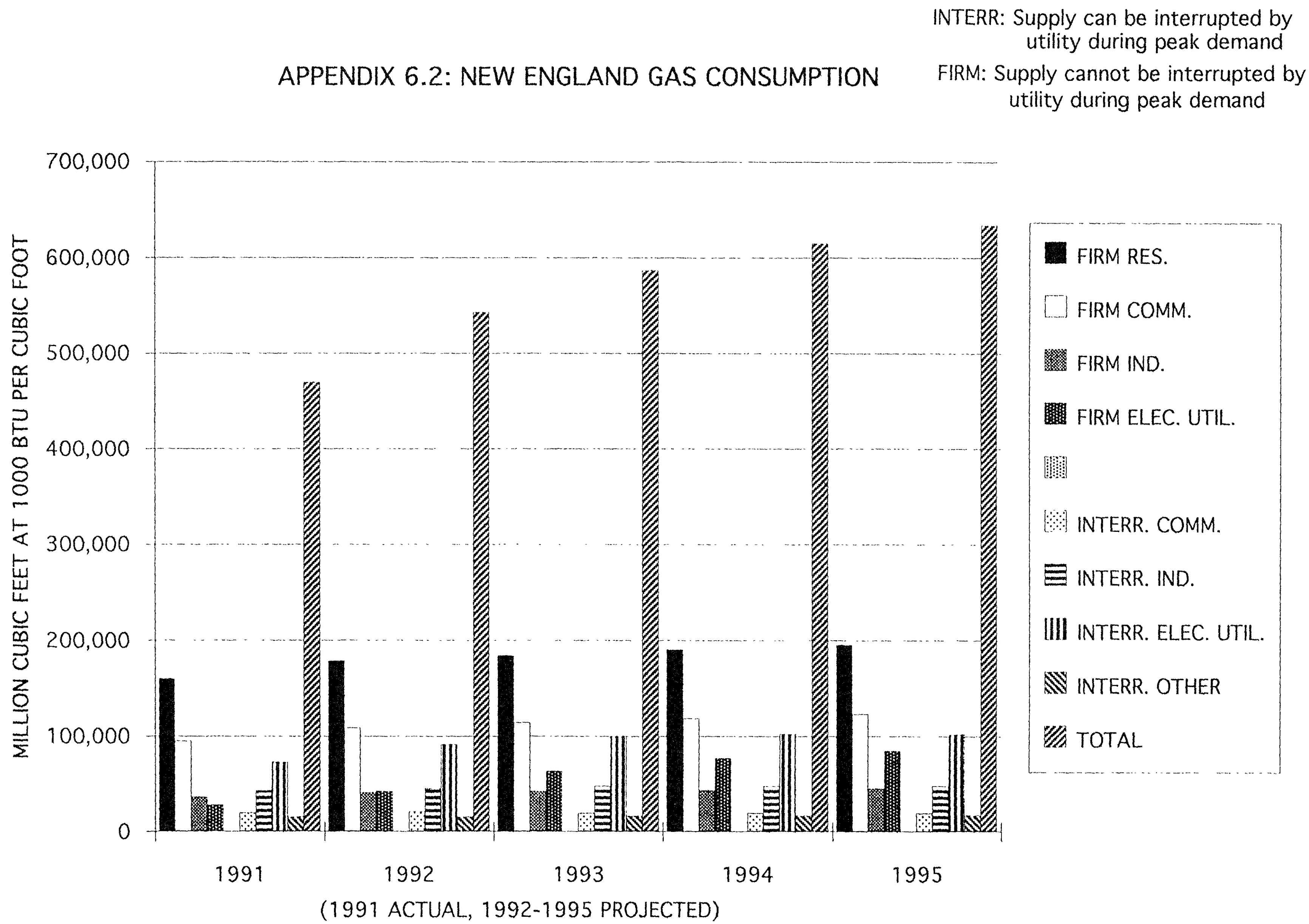


1992
1996
APPENDIX 5.5: TECHNOLOGY ENERGY EFFICIENCY COMPARISON
12. Slippery ice with heat recovery and cold air distribution
11. Ice with heat recovery and cold air distribution
10. Chilled water with heat recovery*
9. High-efficiency centrifugal central chiller with heat recovery
8. Chilled water
7. Baseline: High efficiency centrifugal chiller
6. Ice with cold air distribution
5. Ice with heat recovery*
4. Slippery Ice*
3. Large rooftop unit
2. Ice*
1. Small rooftop unit, 10 years old
TECHNOLOGY
12
11
10
9
8
7
6
5
4
3
2
1
0
20
40
60
80
100
120
140
160
180
ENERGY USE (% OF BASELINE UNIT)

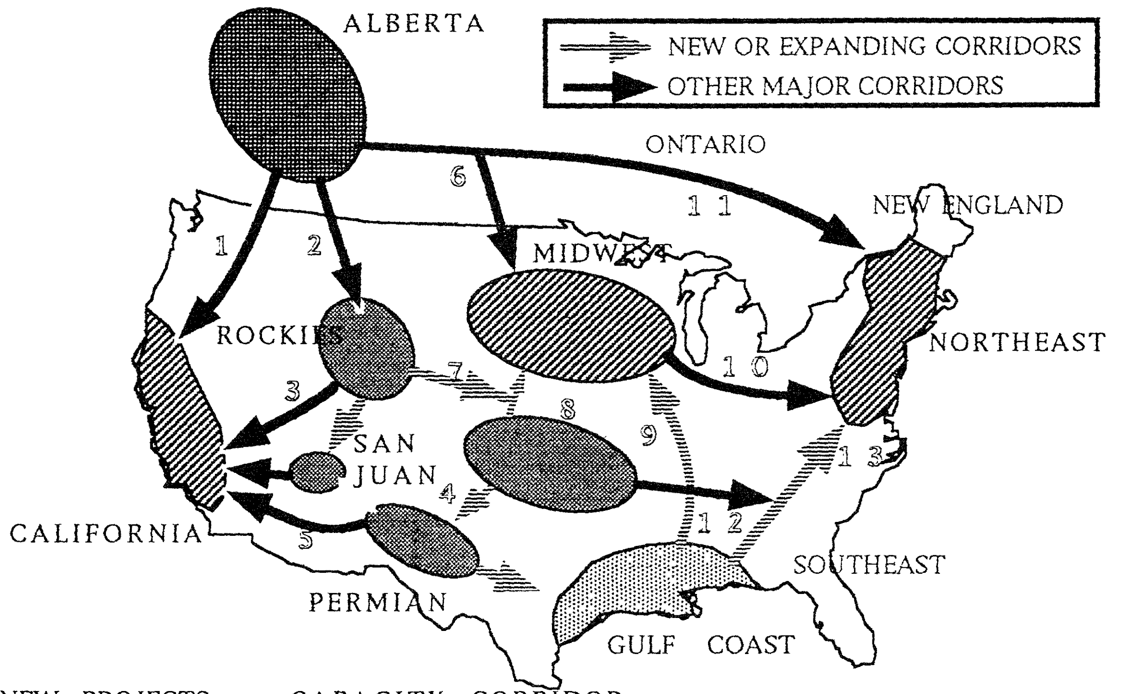
APPENDIX 6.1: UNITED STATES GAS CONSUMPTION



APPENDIX 6.2: NEW ENGLAND GAS CONSUMPTION



APPENDIX 6.3: MAJOR U.S. PIPELINES



NEW PROJECTS TO NORTHEAST	CAPACITY (MMMcfd)	CORRIDOR (SEE ABOVE)
LEBANON EXT.	480	10
TGT EXT.	260	10
CNG	390	10
TRANSCO	280	10
TEXAS EA./CNG	350	10
TRANSCANADA	900	11
IROQUOIS	650	11
EMPIRE STATE	150	11
NIAGARA SPUR	130	11

MAJOR MARKETS
MAJOR SUPPLY BASINS
COMBINATION SUPPLY BASIN & MARKET
1 2 CORRIDOR NUMBERS

Source: "EIA Sees U.S. Gas Grid Meeting Demand in 2000," Oil & Gas Journal, Aug. 3, 1992.

APPENDIX 6.4: STORAGE RESEVOIRS-GEOLOGICAL DATA, ORIGINAL CONTENT OF RESEVOIRS, 1992							
State	No. of Resevoirs	Dry Gas	Oil & Gas	Oil	Aquifer	Other	Total Capacity MILL. CU. FT.
Arkansas	4	4	0	0	0	0	38,000.00
California	9	3	6	0	0	0	506,515.70
Colorado	12	5	6	0	0	0	130,404.70
Illinois	33	8	3	0	22	0	957,229.40
Indiana	28	17	0	0	10	1	164,829.90
Iowa	8	0	0	0	8	0	354,500.00
Kansas	15	14	0	0	0	1	197,673.50
Kentucky	20	18	1	0	1	0	209,433.70
Louisiana	9	7	0	0	0	2	571,524.70
Maryland	1	1	0	0	0	0	64,770.00
Michigan	50	43	4	0	0	3	1,010,327.10
Minnesota	1	0	0	0	1	0	20,000.00
Mississippi	7	3	0	0	0	4	108,799.90
Missouri	1	0	0	0	1	0	45,000.00
Montana	5	5	0	0	0	0	373,960.00
Nebraska	2	1	1	0	0	0	93,312.00
New Mexico	3	2	0	0	1	0	91,353.30
New York	21	21	0	0	0	0	168,975.60
Ohio	22	22	0	0	0	0	553,672.50
Oklahoma	12	10	1	0	0	1	369,528.00
Oregon	2	2	0	0	0	0	11,148.00
Pennsylvania	58	58	0	0	0	0	726,868.10
Texas	23	5	7	5	0	6	420,406.20
Utah	2	0	0	0	2	0	5,388.70
Washington	2	0	0	0	2	0	34,018.00
West Virgina	37	34	3	0	0	0	503,973.90
Wyoming	8	7	0	0	1	0	104,815.10
Totals	395	290	32	5	49	19	7,836,428.00
Source: Engineering technical Note," US-92-2-1, May 1992, American Gas Association							

APPENDIX 6.5: COMMISSION JURISDICTION OVER LDC CONSTRUCTION, ACQUISITION, LEASING OF STORAGE FACILITIES

State	Commission Approval Required for Construction of Storage Facilities	Commission Approval Required for Acquiring or Leasing Storage from Interstate or Intrastate Pipeline	Commission Approval Required for Acquiring or Leasing Storage from Other Distributors	Commission Approval Required for Acquiring or Leasing Storage from Other Sources			
Alabama	Y*a,b	*	__	__			
Alaska	N*	Y	N	N			
Arizona	N	N	N	N			
Arkansas	Y*a,b	N	N	N			
California	Ya,b	__	Y	__			
Colorado	Ya,b	N	N	N			
Connecticut	N	N	N	N			
Delaware	N	N	N	N			
Florida	N	N	N	N			
Georgia	N	N	N	N			
Idaho	N	N	N	N			
Illinois	Ya,b	N	Y	N			
Indiana	Y	N	Y	N			
Iowa	Y a	N	N	N			
Kentucky	Y a,b	N	N	N			
Louisiana	N	N	N	N			
Maine	Y a,b	Y	Y	Y			
Maryland	N	N	N	N			
Massachusetts	N	N	N	N			
Michigan	Y a,b	N	N	N			
Mississippi	Y a,b	Y	Y	Y			

APPENDIX 6.5 (Cont): COMMISSION JURISDICTION Of LDC CONSTRUCTION, ACQUISITION, LEASING OF STORAGE FACILITIES

	Commission Approval Required for Construction of Storage Facilities	Commission Approval Required for Acquiring or Leasing Storage from Interstate or Intrastate Pipeline	Commission Approval Required for Acquiring or Leasing Storage from Other Distributors	Commission Approval Required for Acquiring or Leasing Storage from Other Sources			
State							
Missouri	N	N	N	N			
Montana	N	N	N	N			
Nevada	Y a,b	N	N	N			
New Hampshire	N	N	N	N			
New Jersey	Y a,b	N	N	N			
New Mexico	N	N	N	N			
New York	Y a,b	N	N	N			
N. Carolina	N	N	N	N			
N. Dakota	N	N	N	N			
Ohio	N	N	Y	N			
Oklahoma	N	Y	Y	Y			
Oregon	N	N	N	N			
Pennsylvania	Y	Y	Y	Y			
Rhode Island	N	N	—	N			
S. Carolina	N	N	N	N			
S. Dakota	N	N	N	N			
Tennessee	Y	Y	Y	Y			
Texas	N	N	N	N			
Utah	N	Y	N	Y			
Vermont	Y a,b	Y	—	—			
Virginia	Y a,b	N	Y	N			

APPENDIX 6.5 (Cont.): COMMISSION JURISDICTION Of LDC CONSTRUCTION, ACQUISITION, LEASING OF STORAGE FACILITIES

State	Commission Approval Required for Construction of Storage Facilities	Commission Approval Required for Acquiring or Leasing Storage from Interstate or Intrastate Pipeline	Commission Approval Required for Acquiring or Leasing Storage from Other Distributors	Commission Approval Required for Acquiring or Leasing Storage from Other Sources			
Washington	Y	N	N	N			
West Virgina	Y a,b	Y	Y	N			
Wisconson	Y a,b	Y	Y	Y			
Wyoming	Y a,b	Y	Y	Y			
	Y=22, N=24	Y=11, N=33	Y=13, N=30	Y=8, N=35			

Source: NRRI survey on state commisssion gas storage policies for local distribution companies, 1990

* Y=Yes; N=No; __+ no answer given, don't know issue never addressed.
a Commission uses a formal proceeding in reviewi ng the application for constructing gas storage facilities.
b Commission issues a certificate of public convenience and necessity in approving the gas storage project.

APPENDIX 6.6: STATES IN WHICH LDCs NEED APPROVAL FROM OTHER STATE OR FEDERAL AGENCIES FOR STORAGE FACILITY CONSTRUCTION

State	Agency				
Alaska	Alaska Department of Environmental Conservation Alaska Department of Natural Resources				
California	Division of Oil & Gas of the California Department of Conservation				
Delaware	Delaware Department of Natural Resources and Environmental Control				
Georgia	Georgia State Fire Marshal's Office				
Idaho	Federal Energy Regulatory Commission (FERC)				
Indiana	Indiana Department of Natural Resources				
Iowa	Iowa Department of Natural Resources				
Kentucky	Kentucky Department of Mines and Minerals				
Maine	Maine Board of Environmental Protection				
Massachusetts	Massachusetts Energy Facilities Siting Council Massachusetts Department of Environmental Protection (MEPA Unit)				
Michigan	Michigan Department of Natural Resources				
Mississippi	Mississippi Oil & GAs Board				
Montana	Montana Oil & Gas Commission				
New Jersey	New Jersey Department of Environmental Protection				
New York	New York State Department of Environmental Conservation				
N. Dakota	FERC (if interstate system)				
Oregon	Oregon Energy Facilities Site Evaluation Council (EFSEC)				
Pennsylvania	Bureau of Oil & Gas Management of the Pennsylvania Department of Enviromental Resources				
Rhode Island	Rhode Island Department of Environmental Management				
Vermont	Vermont Environmental Agency				

APPENDIX 6.6 (Cont.): STATES IN WHICH LDCs NEED APPROVAL FROM OTHER STATE OR FEDERAL AGENCIES FOR STORAGE FACILITY CONSTRUCTION

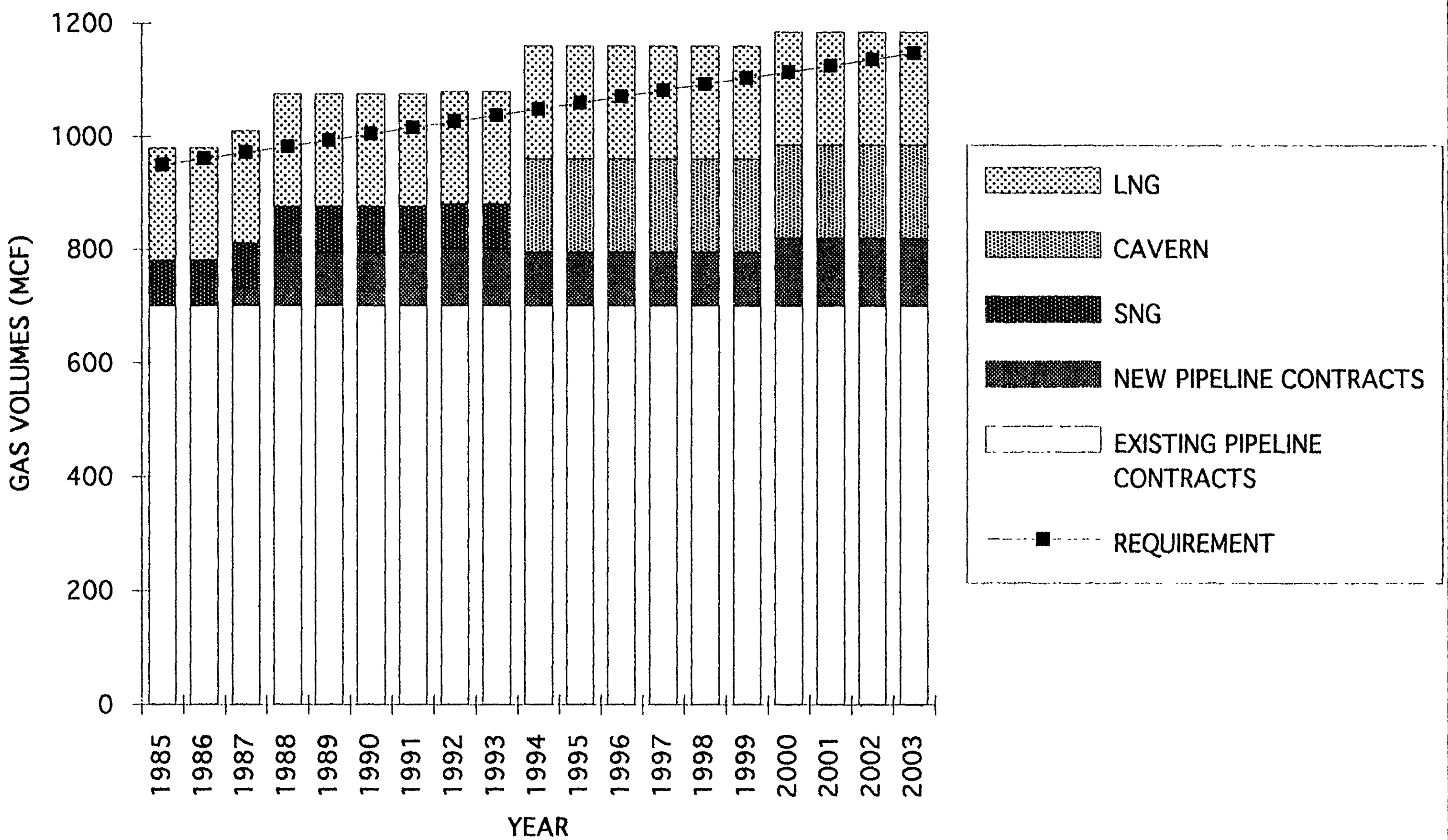
State	Agency				
Washington	Washington Energy Facilities Siting Council				
Wisconson	Wisconson Department of Natural Resources				
Wyoming	Wyoming Oil & Gas Conservation Commission Wyoming Department of Environmental Quality				

APPENDIX 6.7: UNDERGROUND CAVERNS FOR LPG MINED IN THE U.S. BY FENIX & SCISSON, INC.			
Client-Location	Capacity Bbls.	Year Completed	Earth Formation
Amoco Oil Company Hammond, Ind.			
Hammond, Ind.	400,000	1984	Limestone
Whiting, Ind.	400,000	1982	Limestone
Baltimore Gas & Electric Co.			
Baltimore, MD.	150,000	1962	Granite
Carolina Pipeline Co.			
York, S.C.	375,000	1976	Granite
Carolina-Transco Propane Co.			
York, S.C.	1,550,000	1979	Granite
Cincinnati Gas & Electric Co.			
Cincinati, Ohio	200,000	1963	Limestone
Columbia Hydrocarbon Corp.			
Siloam, Ky	210,000	1959	Shale
Siloam, Ky	85,000	1959	Shale
Continental Oil Co.			
Ponca City, Okla	300,000	1961	Limestone
Mont Vernon, Mo.	80,000	1964	Limestone
Griffith, Ind.	300,000	1970	Shale
Dixie Pipeline Co.			
Milner, Ga.	325,000	1965	Granite
E.I. dupont de Nemours & Co.			
Gibbstown, N.J.	180,000	1968	Granite
Esso Standard Oil Co.			
Linden, N.J.	150,000	1957	Shale
Linden, N.J.	150,000	1957	Shale
Linden, N.J.	100,000	1958	Shale
Linden, N.J.	125,000	1958	Shale
Linden, N.J.	150,000	1958	Shale
General Facilities, Inc.			
Wood River, Ill.	100,000	1962	Limestone
Hydrocarbon Transportation Inc.			
Des Moines, Iowa	100,000	1970	Shale
Morris, Ill.	150,000	1971	Shale
Laclede Gas Company			
Florissat, Mo.	785,000	1972	

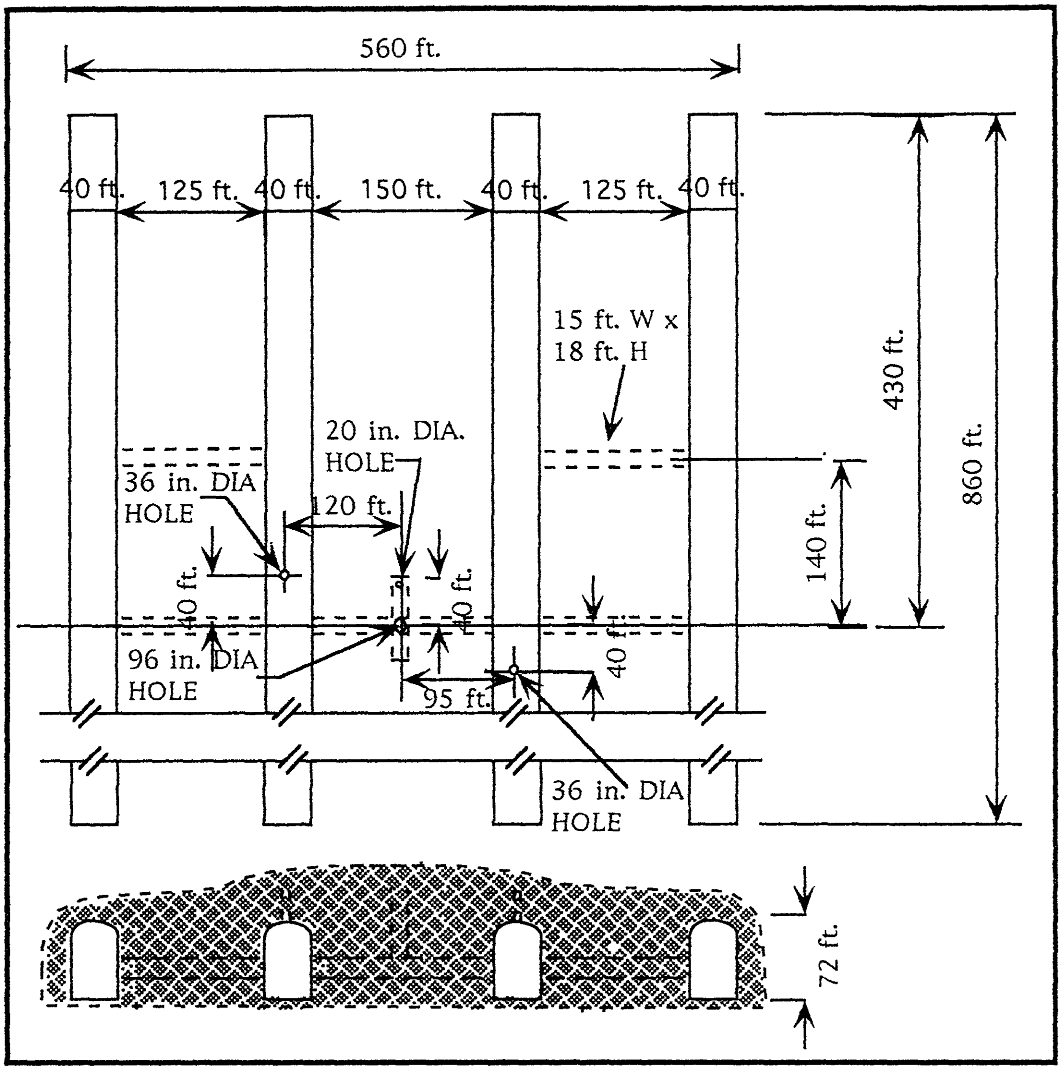
APPENDIX 6.7 (Cont): UNDERGROUND CAVERNS FOR LPG MINED IN THE U.S. BY FENIX & SCISSON, INC.			
Client-Location	Capacity Bbls.	Year Completed	Earth Formation
Mapco, Inc.			
Greenwood, Neb.	400,000	1963	Limestone & Shale
Iowa City, Iowa	400,000	1963	Shale
Iowa City, Iowa	220,000	1967	Shale
Farmington, Ill	400,000	1965	Shale
Metropolitan Utilities District			
Omaha, Neb.	150,000	1960	Shale
Omaha, Neb.	250,000	1963	Limestone
Norsk-Hydro			
Herdya, Norway	300,000	1967	Limestone
Northern Natural Gas Products Co.			
Des Moines, Iowa	60,000	1967	Limestone
Des Moines, Iowa	180,000	1967	Shale
Shell-Berre			
Rouen, France	200,000	1966	Chalk
Rouen, France	60,000	1966	Chalk
Shell Oil Co.			
Wood River, Ill.	520,000	1960	Limestone
Wood River, Ill.	260,000	1961	Limestone
Signal Oil & Gas Co.			
Erskine, Minn.	300,000	1962	Dolomite
Sinclair Oil & Gas Company			
Seminole, Okla.	110,000	1954	Shale
Demopolis, Ala.	140,000	1956	Chalk
Demopolis, Ala.	225,000	1956	Chalk
Standard Oil Co. (Ohio)			
Lima, Ohio	425,000	1970	Shale
Toledo, Ohio	175,000	1970	Shale
Sun Oil Company			
Marcus Hook, Pa.	250,000	1958	Granite
Marcus Hook, Pa.	250,000	1960	Granite
Marcus Hook, Pa.	400,000	1961	Granite
Marcus Hook, Pa.	75,000	1962	Granite
Marcus Hook, Pa.	1,185,000	1976	Granite

APPENDIX 6.7 (cont): UNDERGROUND CAVERNS FOR LPG MINED IN THE U.S. BY FENIX & SCISSON, INC.			
Client-Location	Capacity Bbls.	Completed	Formation
Sunray DX Oil Company			
Tulsa, Okl.	250000	1966	Shale
Texas Eastern Products Pipeline Co.			
Watkins Glen, N.Y.	1300000	1984	Siltstone
Texas Eastern Transmission Corp.			
Middletown, Ohio	185000	1959	Shale
Middletown, Ohio	235000	1959	Shale
Middletown, Ohio	160000	1959	Shale
Middletown, Ohio	190000	1959	Shale
Middletown, Ohio	225000	1960	Shale
Middletown, Ohio	425000	1961	Shale
Middletown, Ohio	425000	1963	Shale
Middletown, Ohio	525000	1974	Shale
Princeton, Ind.	175000	1961	Shale
Greenburg, Pa.	100000	1964	Shale
Monee, Ill.	200000	1972	Shale
Monee, Ill.	115000	1982	Shale
Greensburg, Pa.	200000	1973	Shale
Seymour, Ind.	220000	1975	Shale
Seymour, Ind.	425000	1976	Shale
Tuloma Gas Products Co.			
Wood River, Ill.	240000	1961	Limestone
Union Light, Heat & Power Co.			
Covington, Ky.	175000	1961	Limestone
U.S. Industrial Chemicals Co.			
Tuscola, Ill.	800000	1964	Limestone & Shale
Warren Petroleum Company			
Breckenridge, Texas	20000	1950	Shale
Breckenridge, Texas	30000	1952	Shale
Eola, Ill.	50000	1953	Shale
Crossville, Ill.	50000	1953	Shale
Calvert City, Ky.	250000	1963	Limestone
Calvert City, Ky.	25000	1963	Limestone
Washington Gas Light			
Burke, Va.	300000	1962	Granite
Williams Brothers Pipeline Co.			
Carthage, Mo.	220000	1967	Shale

APPENDIX 6.8: BUGC LONG TERM PEAK DAY SUPPLY VS REQUIREMENT FORECAST



APPENDIX 6.9: PROPOSED CAVERN LAYOUT



Source: Brooklyn Union Gas Company, Excerpts from Geotechnical Feasibility Report "Mined Natural Gas Storage Cavern at JFK International Airport Site." Prepared by Fenix & Scisson, February, 1991.

APPENDIX 6.10: CAVERN DEPTH OPTIMIZATION ANALYSIS

FOR $20 \times 10^6 m^3$ (st) [$700 \times 10^6 ft^3$] STORAGE VOLUME

AT INJECTION/WITHDRAWAL RATE OF $4.7 \times 10^6 m^3/d$ (st) {$165 \times 10^6 ft^3/d$}

DEPTH m	DEPTH (ft)	EXCAVATED VOLUME $10^3 m^3$	EXCAVATED VOLUME ($10^6 ft^3$)	NUMBER & SIZE OF SHAFTS 183CM/91CM	COST IN U.S. DOLLARS (MILLIONS) Shafts	Excavation	Compressor Station	Feasibility Study	Project Support	Conversion & Testing	Eng. & Constr. Fees	Cushion Gas	Total
457	(1500)	523	(18.46)	2 OF 4	25.3	62.2	8.8	1.00	0.50	2.0	7.98	0.6	108.4
609	(2000)	370	(13.08)	2 OF 4	30.2	53.1	9.0	1.00	0.50	3.0	7.74	0.5	105.0
(*)762	(2500)	275	(09.76)	2 OF 3	33.6	47.4	9.1	1.25	0.75	3.5	7.64	0.4	103.6
914	(3000)	221	(07.80)	2 OF 2	35.4	44.3	9.8	1.50	0.75	4.0	7.66	0.3	103.7

Note: * Denotes optimum Depth

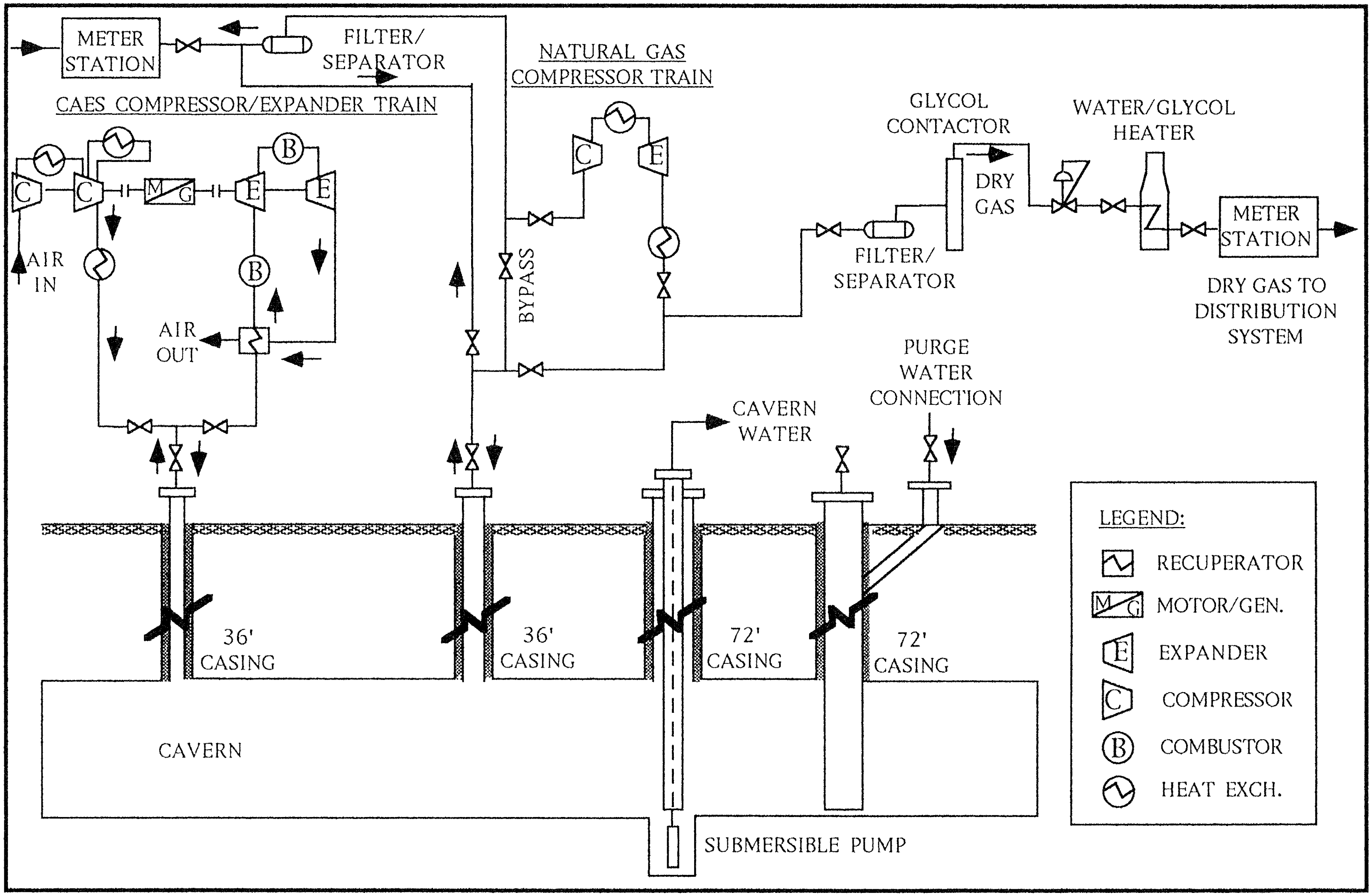
Source: Brooklyn Union Gas Company, Excerpts from: Geotechnical Feasibility Report Mined Natural Gas Storage Cavern at JFK International Airport Site, Prepared by: Fenix & Scisson, Febuary, 1991

APPENDIX 6.11: SUMMARY OF ROCK PROPERTIES ENGINEERING PROPERTY	Source*	AVERAGE VALUE
Unconfined Compressive Strength		
A. Numerical Average of all 75 samples	(UI & US)	9,740 psi
B. 22 Samples below 1200 feet for which strain exceeded 0.2% at failure	(UI)	16,800 psi
C. 29 Samples below 1200 feet which failed prematurely and had strain less than 0.2% at failure	(UI)	9,000 psi
Modulus of Elasticity	(US)	7.513×10^6 PSI
Poisson's Ratio	(US)	0.258
Brazilian Tenslie Strength (Gneiss)		
A. Load applied parallel to foliation	(UI & US)	1,184 psi
B Load applied perpendicular to foliation	(UI & US)	2,21 psi
Unit Weight (Gneiss)	(UI)	172 PCF
Bulk Density (Gneiss)	(US)	2.08%
Permeability		
Primary	(US)	0
Secondary (2200-2800')	(F)	1.32×10^{-6} cm/sec
Rock Hardness Propertiies (Gneiss)		
Shore Scleroscope	(UI)	82.5
Schmidt Hammer (L-Type)	(UI)	51.3
Abrasion Hardness (taber)	(UI)	3.042
Water Immersion Slaking	(US)	No Effect
Gas Immersion	(US)	No Effect
Thermal Conductivity (Gneiss)		
A. Parallel to foliation	(TT)	1.54 BTU/Hr x Ft x F°
B. Perpindicular to foliation	(TT)	1.20 BTU/Hr x Ft x F°
Specific Heat	(TT)	0.08 BTU/lb-F°
Stress Magniyudes - In Situ Fracturing		
Sv Vertical Stress (calc. at 2500 ft Depth)	(h)	2900 psi
Sh Minimum Horizontal Stress	(h)	3000 psi
Sn Overall Minimum Stress	(h)	2400 psi
SH Maximum Horizontal Stress	(h)	5150 psi

*Key
- F Univ. of Illinois Testing Laboratories
- TT Terra Tek
- US United States testing Company
- H Dr. Haimson
- F Sidney Fox

Source: Brooklyn Union Gas Company, Excerpts from: Geotechnical Feasibility Report Mined Natural Gas Storage Cavern at JFK International Airport Site Prepared by: Fenix & Scisson, February, 1991

APPENDIX 6.12: CONCEPTUAL FLOWSHEET OF DUAL PURPOSE FACILITY



Source: Brooklyn Union Gas Company, Geotechnical Feasibility Report Mined Natural Gas Storage Facility at JFK International Airport Site. Prepared by Fenix & Scisson, February, 1991.

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