TOBER

THE FEASIBILITY OF CONVERTING
MARLBORO COLLEGE
TO ENERGY SELF-SUFFICIENCY
USING ALTERNATE SOURCES OF ENERGY

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II FOREWARD

For twelve weeks during the summer of 1974, eight students carried out the research which is summarized in this report. The study was funded by a grant (GY-11443) from the National Science Foundation under the Student Originated Studies section of the Student Oriented Program.

The idea to study whether it is feasible for Marlboro College to become energy self-sufficient arose during the question and answer period following a presentation given by James Stiles (Project Director) in the Environmental Seminar course. Following the seminar, a grant proposal was submitted and approved, and the study was conducted. Now, as this report is being written, a new proposal is being submitted to the National Science Foundation. If approved, this grant will support the construction of a wood-solar heating demonstration project to be installed on one college dormitory.

What is noteworthy about this study is not the subject matter of alternate energy or even the findings that energy self-sufficiency is feasible, but that these findings are the result of student-directed research and that the students will have a major share of the responsibility for the future implementation of these systems. It is particularly significant that these findings are not restricted in application to Marlboro College, for the systems defined in this report are expected to have wide applicability which will extend to many other institutions and small communities.

The publication of this report is but a first step in the process of converting Marlboro College to energy self-sufficiency. The systems and ideas contained in this report must be pursued vigorously if alternate energy is to become a reality at the college. As Professor William Heronemus, of the University of Massachusetts, said at a recent symposium at Marlboro College, widespread use of alternate energy "is a lead pipe cinch if we want it to happen...And all that is required is just for enough people to finally admit...if it is what we have to have thirty years from now, if we will get off our backsides and get to work, it is what we can have six years from now." Students at Marlboro College have begun that work.

(Foreward written by John Hayes, Faculty Advisor.)

III INTRODUCTION

The purpose of this study was to determine whether it is scientifically, technologically, and economically feasible for Marlboro College to become energy self-sufficient using alternate sources of energy available on campus.

This is not an adequate definition of the project's scope, for it does not provide answers to questions such as, "Is the paper produced elsewhere and brought to the campus a valid source of energy? To be self-sufficient, wouldn't the college have to export energy to society to replace that consumed as imported paper?"

It was decided that to use any material as an energy source it has to be produced on campus or, if produced elsewhere, it has to be brought to the campus for reasons other than supplying energy. In addition, if there were a method of disposal of that material which was more economical, then it would not be used as an energy source.

Having defined valid sources of energy, it was necessary to determine which types of usage would be investigated for replacement by alternate energy systems. For example, should the fuel used by college-owned motor vehicles while operating on campus be provided by an alternate energy system?

It was decided to limit consideration to supplying heat and electricity, as these are the most critical energy needs of the college and represent by far the largest forms of energy consumption. The goal of this project, then, was to design the most economical alternate energy systems which could provide 100% of the college's heating and electrical energy demand.

On the campus there are five potential sources of energy: wood, flowing water, organic wastes, sun, and wind. Each of these sources was investigated to find the most cost-effective combination. The project participants and their responsibilities for the investigations of these sources were as follows:

James Stiles------Project Director; member, energy conservation group.

Nanda Fleming-----Chairwoman, meteorology group; bibliographer.

Kenneth MacLeish--Chairman, wind power and electrical generation group; member, solar power group.

Edward Nelbach----Chairman, water power group; member, organic wastes and electrical generation groups.

John Nevins--------Chairman, Forestry Group; member, Solar Energy Group; member, Organic Wastes Group.

Leonard Slosky----Chairman, organic wastes group; member, forestry group.

Douglas Smith-----Chairman, solar power group; member, wind power and water power groups.

Ingrid Wendt------Chairwoman, energy conservation group; economist for every group.

We would like to express our appreciation to everyone who assisted us in our work. Dr. Larry Gay, author of Heating With Wood, provided invaluable help on wood energy. Robert Kagan's considerable experience with research projects often allowed us to avoid potentially serious problems. Rory Goff provided assistance in several areas, most notably with energy conservation and editing of reports. Dr. James Tober spent many hours helping with economic theory. Piet van Loon helped with building specifications and provided records of energy use. Halsey Hicks pointed out several inconsistencies in the arguments. Malcolm Moore provided many names and references on alternate energy research. Dr. John MacArthur, builder of a wind-energy conversion device and an electric car, provided computer assistance, checked some of the equations used, and was generally available at any time for discussions on both the theoretical and practical aspects of alternate energy systems. Dr. John Hayes, Faculty Advisor, devoted many hours to the administration of the project and was available for consultation at any time. Special thanks are due Benjamin Hoffman, Chief of Land Management for the State of Vermont, and Roy Burton, State Forester, for instruction in the use of the Patunoff Forest Inventory System.

Finally, we would like to thank the many people who provided us with newspaper clippings, ideas, and advice, and whose interest in the project gave us much encouragement.

IV ENERGY CONSERVATION

Introduction

A strong, aggressive program for energy conservation at Marlboro College can yield substantial results, but reducing energy consumption is not a direct goal of this project. This is because reduced energy consumption would have an approximately equivalent effect on the economics of both conventional and alternate energy systems. Consequently, only secondary effort was placed on research into methods of conserving energy.

However, there are several reasons for studying energy conservation. One, alternate energy systems are characterized by high capital costs and low operating costs when compared to conventional systems. Since large amounts of capital are difficult to obtain, even though alternate energy systems might cost less over a twenty year period, a lack of capital might dictate a continued use of conventional systems. If conservation reduces the size of the necessary alternate energy system, it may also reduce the capital expenditure to a more obtainable size.

Two, the ecological impact of removing large amounts of wood or changing the land from its natural state can increase in a way that is out of proportion to the increased amount of wood used or land changed. That is to say, removing twice the amount of wood, for example, may well more than double the impact of removing the original amount, possibly to the point of depleting the resource. This impact is also important because the college depends on its land as part of its cultural and aesthetic environment, as well as a potential source of energy.

Three, if it is assumed that at the present rate of consumption there are one million years of energy resources left on earth, at the present 5% yearly energy growth rate, that one million years of energy reserves will be used up in a mere 270 years! It is felt that not only should the college strive to minimize capital expenditure but it should also strive to reduce energy consumption to the lowest possible level.

Most of the literature on energy conservation has been directed towards residential, business, or industrial applications. Very little research has been done for institutions such as Marlboro College so information on energy conservation must be carefully examined for its applicability to this situation. Generally, information on industrial conservation measures is not applicable, but energy conservation techniques for small businesses and residences are appropriate for the college in many cases. Most structures on campus are constructed just like homes, except in cases such as the Dining Hall which has a construction typical of many small businesses. Use patterns at the college differ from those of either residences or small businesses, but not seriously, so the differences can reasonably be ignored.

Heat Saving Methods

More than 90% of the college's energy use is for heating, and a large portion of this is wasted. The single most important way to reduce this waste is to properly maintain the heating plants of the buildings.

A furnace that is operating maximally combusts fuel at about 80% efficiency. Most well-maintained furnaces, such as most of those at the college, operate at 65-70% efficiency; however, some old and ill-maintained units operate at an efficiency that varies anywhere from 50 to 35% or even less. An excellent way to decrease energy demand for heating, then, is to increase combustion efficiency, a doubling of efficiency yielding a 50% reduction in fuel use. These increases in efficiency can be accomplished by cleaning and adjusting burners, cleaning filters, replacing worn out components and systems, and performing other cleaning and maintenance of the system.

An obvious way to conserve heat is to lower thermostat settings. This is true for two reasons: first, conductive heat loss is dependent on the temperature difference between the inner and outer surfaces, and when this difference is reduced, conductive heat loss is reduced at the same rate. For each one degree Fahrenheit that a thermostat is reduced, an annual saving of 3% can be expected, most of this by reducing conductive heat loss. Second, the more inside air is heated, the more heat is lost when it leaks out, and when cold air leaks in, the more it must be heated to maintain the thermostat setting.

Building maintenance is equally important for conserving energy. Closing cracks in walls, around windows and doors is perhaps the most important building improvement to cut heating demand. Infiltration of cold air and the attendant exfiltration of warm air normally accounts for 15 to 30% of a heating bill, and frequently more. It is important to have some air exchange in a building, otherwise unpleasant odors can accumulate. However, in most old buildings there is much more air exchange than is needed. Most of the buildings on campus are relatively old with many of them predating the founding of the college in 1946.

Another facet of the infiltration-exfiltration problem that is commonly ignored is the effect of this air exchange on building humidity. When the moist air inside a building is replaced by cold, dry air from outside, the humidity drops drastically, causing discomfort by drying out mucous membranes and by causing greater body cooling because of increased perspiration evaporation. Thus, greater comfort can be achieved at a lower temperature in a moist building.

Another major source of inefficiency is unequal heat distribution. If some parts of a building are normally cold, to maintain comfort levels the rest of the building is frequently over heated. As a result, what often happens is that some rooms are heated to about 85 degrees all winter long. This problem would be alleviated by better control of heating, the kind of control that is accomplished with electric heat. Electric heat is not the solution though, due to the inherent inefficiency of electrical generation and transmission. Rather, if the heating system cannot be easily adjusted, a major effort should be made to reduce heat loss from the coldest rooms. By doing this, the temperature can be lowered in the rest of the building while maintaining a comfortable temperature in all rooms.

Retrofitting insulation can bring additional heating savings beyond a simple decrease in conductive heat loss through ceilings and walls. The first type of saving is brought about by the increased temperatures of inside surfaces and the attendant reduction in radiative heat losses from the body. Radiative heat losses from an object increase to the fourth power of the change in absolute temperature so when there are substantial temperature differences between two surfaces, radiation losses can become significant as in the case of losses through a single sheet of window glass. When the outside temperature is 0 degrees Fahrenheit, the inside surface of the glass is approximately 19 degrees. Installing a simple insulating shutter over such a window can raise the inside temperature to almost 60 degrees in a 70 degree room. This means that in practical terms it would be possible to leave the building at a lower temperature and yet maintain an identical level of comfort.

The second indirect effect of increased insulation is related to the heat that is supplied by solar insolation, body heat of people in the building, waste electrical heat, and other sources. These sources supply a base load of heat independent of the furnace. About 10% of the heat in most of the college dormitories is generated in this way. However, if the overall amount of heat supplied in these dormitories were decreased by 30%, for example, the real drop in demand on the furnace would be greater.

100% = percentage of heat presently used

90% = percentage of heat supplied by furnace at present

30% = percentage of heat that can be conserved

[90 - 30]/[100 - 30] = percentage of heat supplied by furnace after conservation

= 85.7%

So, no longer is the furnace supplying 90% of all heat going into the dormitory, but rather 85.7%

Electricity Saving Methods

Electricity use will probably prove more difficult to reduce than heating demand. Lights can be used less and only where needed, walls can be painted white to increase reflectance, and appliance use can be reduced, but these will likely yield only small energy savings. A possible drawback to this conservation is the fact that all electricity ultimately degrades into heat. But conserving electricity even during the heating season is still worthwhile despite the fact that the degraded electricity supplies heat since electricity is a higher grade of energy than heat and its production is inefficient. Thus, there are more efficient and less costly methods of providing heat.

There are some instances where conserving electricity can be particularly worthwhile. For example, a clothes dryer uses about 2 KWH for one load, very little of which is recovered since the heated air cycled through the dryer is exhausted outside. During much of the year, clothes can be dried outside, saving a considerable amount of energy, and during the other months of the year, dryers could be used only for full loads, yielding a further saving. It is possible that from this one source alone, a 5% electrical energy saving could be realized.

The last energy conservation method to be considered in this report is the installation of energy conserving devices such as self-extinguishing light switches, fluorescent light fixtures, and low volume shower heads. The economic feasibility of these devices can be determined by comparing the costs of the devices installed with the amount of energy, and therefore money, that will be saved by employing them. Take as an example the self-extinguishing light switch. If the value of the energy saved is greater than or equal to the installation cost, then that switch should be installed:

$$\$9.95 = \text{cost of switch}$$

$$\$5.00 = \text{installation cost}$$

$$\$0.037 = \text{cost of 1 KWH in 1974}$$

If there are three 150 W light bulbs (a total of 450 W) on one switch, the break even point is reached when

$$\$9.95 + \$5.00 = \$0.037/\text{KWH} \times 0.45 \text{ KW} \times N \text{ hr}$$

$$N = 890 \text{ hr}$$

So, if on the average day the switch saves three hours of operation, it will take 300 days, or about ten months, to repay the original investment. This would certainly be worthwhile, since such a switch will last many years beyond the initial ten months.

Conclusions

This report contains several relatively uncommon ideas for energy conservation, and, for the most part, it is a brief summary of other more complete works which are listed in the bibliography. It was intended to be no more than a summary since a complete description of energy conservation methods is beyond the scope of this report. But it is recommended, for reasons listed in this section, that a thorough study of energy conservation for specific buildings at Marlboro College be undertaken before installation of any alternate energy systems.

It is felt that a 30% reduction in heat energy and a 20% reduction in electrical energy might be realized. Any reduction in energy usage will be the result of not only a concerted effort to add insulation,to better maintain buildings, and so forth, but also a vigorous campaign to develop an energy-conserving consciousness among the members of the college community.

V SOLAR ENERGY

Introduction

Typically, a report on solar energy will begin with statements such as: "The solar radiation falling upon the 385 acres owned by Marlboro College in the course of a year is roughly 6.5×10^{12} BTU. The energy used by the college in one year for heating is 1.6×10^{10} BTU. Placing these two figures in a ratio, the heating requirement is 0.25% of the available solar energy." All of the preceding statements are true, but this simple ratio may be misleading, because even though a large amount of radiation is received, it is very diffuse. This section will deal specifically with the problems involved in capturing this diffuse radiation.

Sunlight can be converted to several different forms of energy. The first part of this section will present the various possibilities for using solar energy. The most promising system will be examined in detail for economic feasibility in the second part.

Available Energy from the Sun

Marlboro College is on the eastern side of the Green Mountains at an elevation of 1600 to 1700 feet above sea level on a south-facing hillside. The climate is typical for northeastern states with warm, humid summers followed by cold, relatively long winters.

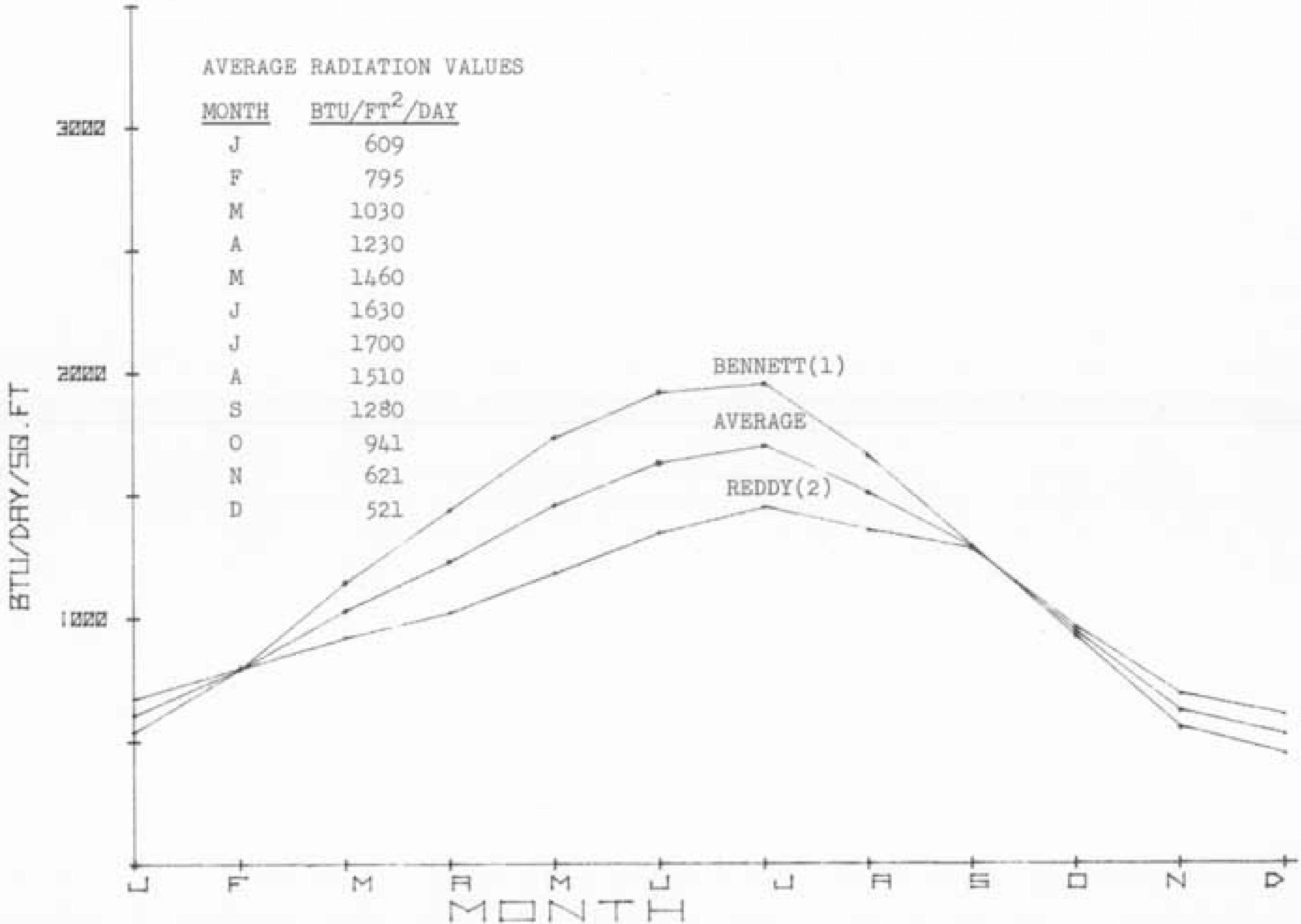
Unfortunately, there are no weather stations nearer than Albany, New York, taking complete weather observations. Even at Albany there is no instrumentation to provide direct measurement of solar radiation. Values for solar radiation were, however, obtained from two separate sources. The first source was a set of maps published by Iven Bennett (1) showing the mean monthly radiation for the United States. The values were converted to the units of BTU/ft^2/day. The second set of values were derived from a method developed by S.J. Reddy (2). This formula (Equation 1 in Appendix 1) takes into account hours of sunshine, number of rainy days per month, mean humidity, and radiation outside the atmosphere.

The results from both of these sources are shown in Figure 1. The average values are also given in tabular form. These values will be used throughout the rest of this section. In the future more information regarding solar radiation will be available as both the University of Massachusetts at Amherst and Williams College in Williamstown, Massachusetts, now have instrumentation for recording solar radiation. The data from these sources will be compared with the estimates used in this report.

Marlboro College Energy Requirement

An assessment of the energy used in any system must be performed before an alternative energy supply can be designed. The college uses energy primarily in two forms, electricity and fuel oil. Electrical energy consumption will be evaluated in

FIGURE 1. AVERAGE DAILY RADIATION: MARLBORO, VERMONT



AVERAGE RADIATION VALUES

MONTH	BTU/FT^2/DAY
J	609
F	795
M	1030
A	1230
M	1460
J	1630
J	1700
A	1510
S	1280
O	941
N	621
D	521

the section on wind energy. Fuel oil is the primary source of low grade heat for most college buildings as only three relatively small structures are heated with electrical resistance heaters.

Data were gathered on fuel oil deliveries for the year 1973. For the months of December, January, and February, the amount of fuel oil delivered was also obtained for the last ten years as these are the most critical months for comparison with available solar insolation. The chemical energy of oil is 147,500 BTU/gal. The efficiency of the oil burners at the college is estimated to be 65%. The data (Table 1) for the central campus are presented. This includes the main campus exclusive of the Persons Auditorium and the buildings further east.

It should be noted that the oil supply figures reflect only the deliveries made to the buildings which do not correspond to the oil consumed in a given month. Unfortunately, there was not enough time to make a more thorough assessment of the heating requirement.

Table 1. Heating Energy Requirement of Marlboro College Main Campus (determined by fuel oil deliveries)

Month	Energy Use/Month 100% Efficiency	Energy Use/Month 65% Efficiency	Energy Use/Day 65% Efficiency
January*	2160**	1410**	45.4**
February*	1940	1260	45.1
March*	1850	1540	40.1
April	1440	934	31.1
May	938	610	19.7
June	935	608	20.2
July	-	-	-
August	-	-	-
September	518	367	11.2
October	794	516	16.6
November	1760	1140	38.1
December*	1550	1280	41.2

** Values in millions of BTU.
* Usage averaged over ten year period.

Review of Utilization Systems

Direct Electrical Conversion

Two devices are available for the direct conversion of sunlight into electricity, the photovoltaic cell (solar cell) and the thermoelectric device. Each operates on a different principle but achieves basically the same result. Sunlight falling upon these devices causes a voltage potential resulting in a flow of electrons through a closed circuit. Currently, both devices operate at about ten percent efficiency or less and are prohibitively expensive.

The high cost of direct conversion devices is directly attributable to the tedious manufacturing techniques for single silicon crystals or complicated procedures used in vacuum deposition of cadmium sulfide. Recently, Tyco Industries has developed a method of producing silicon crystal ribbons which may greatly reduce the cost of solar cells. Other research is being undertaken in simplifying vacuum deposition techniques for the cadmium sulfide solar cell. However, full-scale production is not expected for five to ten years.

The use of direct conversion devices is quite attractive due to the simplicity of system design and lack of maintenance costs. Should the price of solar cells be drastically reduced, Marlboro College would be an ideal location for their installation, due to the requirement of a large land area for generation of significant amounts of electricity.

In addition to the manufacturing problems of direct energy conversion, there is a power storage problem for use during periods of little or no sun. Various systems have been developed, or are in the process of being developed, for the storage of electrical power. Most of the existing systems are only economical in areas where conventional power is not available. Work is now being done on high capacity batteries, fuel-cell systems with storage in hydrogen, and flywheel storage. These systems are not expected to be widely employed in the next several years.

Direct electrical conversion systems are definitely a very promising technology of the future. When the solar cell becomes economically competitive, plant size will probably not be an economic factor. Thus, Marlboro College will be in an excellent position to employ these devices.

Concentrating Heliothermic Collectors

Collectors which concentrate the energy of the sun can be divided into two classes, those which must track the sun continuously (conical parabolic mirrors) and those which only need to be adjusted every two or three days for the changing declination of the sun (parabolic troughs or cylinders). Both are suitable for production of high grade heat (300 to 1000 degrees Fahrenheit) which can be used to produce steam to drive engines which, in turn, could drive generators to produce electricity.

Concentrating collectors were rejected as not being suitable for the college for a variety of reasons. The production of electricity in this manner has not been shown to be economically competitive with conventional sources. As with direct electrical conversion, there is the problem of storage for use during dark periods, and the tracking provision increases the cost of the collectors and requires constant maintenance and adjustment by plant personnel. One possibility for an inexpensive concentrating collector is a design being investigated by Roland Winston (3). This collector, working on the same principle as that of the eye of the horseshoe crab, combines many advantages of the flat plate and concentrating collectors. But, once again, more development is needed.

Flat Plate Collector Systems

The flat plate collector was determined to be the most suitable for the college's needs. The heat obtained from this system would yield low-grade heat (100 to 180 degrees Fahrenheit), and could be easily adapted to the existing heating system. The entire system would consist of a field of collectors, a thermal storage system coupled by heat exchangers, a regulating system, an auxiliary heat source, and the existing hot water circulating systems in the various buildings. Figure 2 is a diagram of the system with wood as the auxiliary heat source.

The Flat Plate Collector System

Design of the Collector

The basic design of the collector is seen in Figure 3. The collector has two transparent covers of a polyvinylfluoride thin film (Tedlar) manufactured by DuPont Company. Tedlar was chosen over glass because of its higher transmission of visible light and its lower cost.

The absorber plate is roll-bond aluminum sheet manufactured by Olin Brass. This plate has water channels between two bonded sheets of aluminum. A selective black surface will be electrochemically deposited upon the panel. The process for applying this coating can be found in the NASA Solar Panel Patent Application (4). Tests carried out by NASA have shown that the average values for absorptivity and emissivity of the selective surface are 0.90 and 0.06. There was some doubt as to whether the selective surface would be cost-effective in the design of the solar collector. It will be shown below, however, that the selective surface is necessary, given the college's 43° latitude.

The support members of the collectors will be made of construction-grade lumber. The back of the collector will be insulated with 3½" of rigid fiberglass. All of the joints will be caulked and waterproofed.

SOLAR~WOOD HEATING SYSTEM

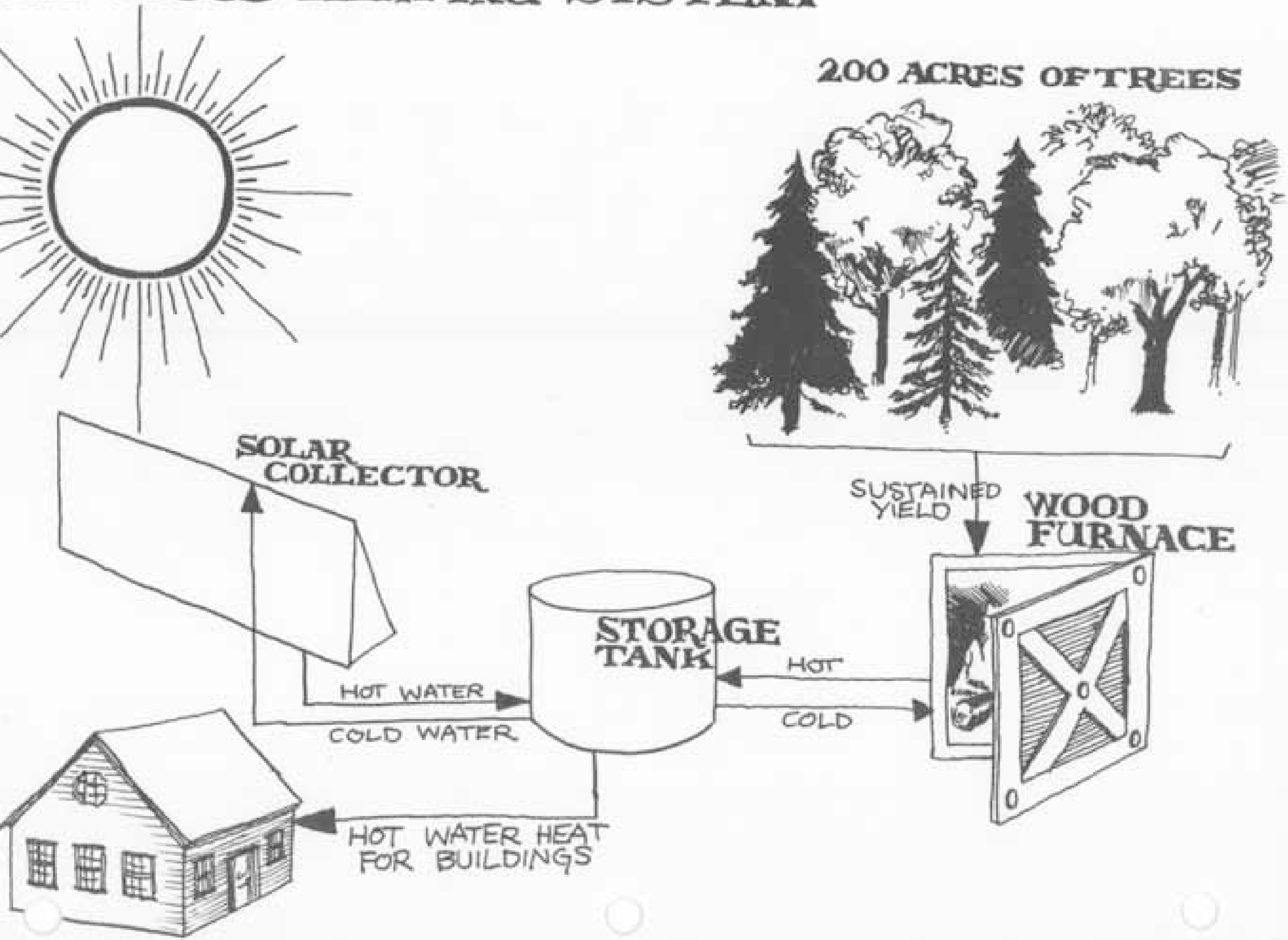
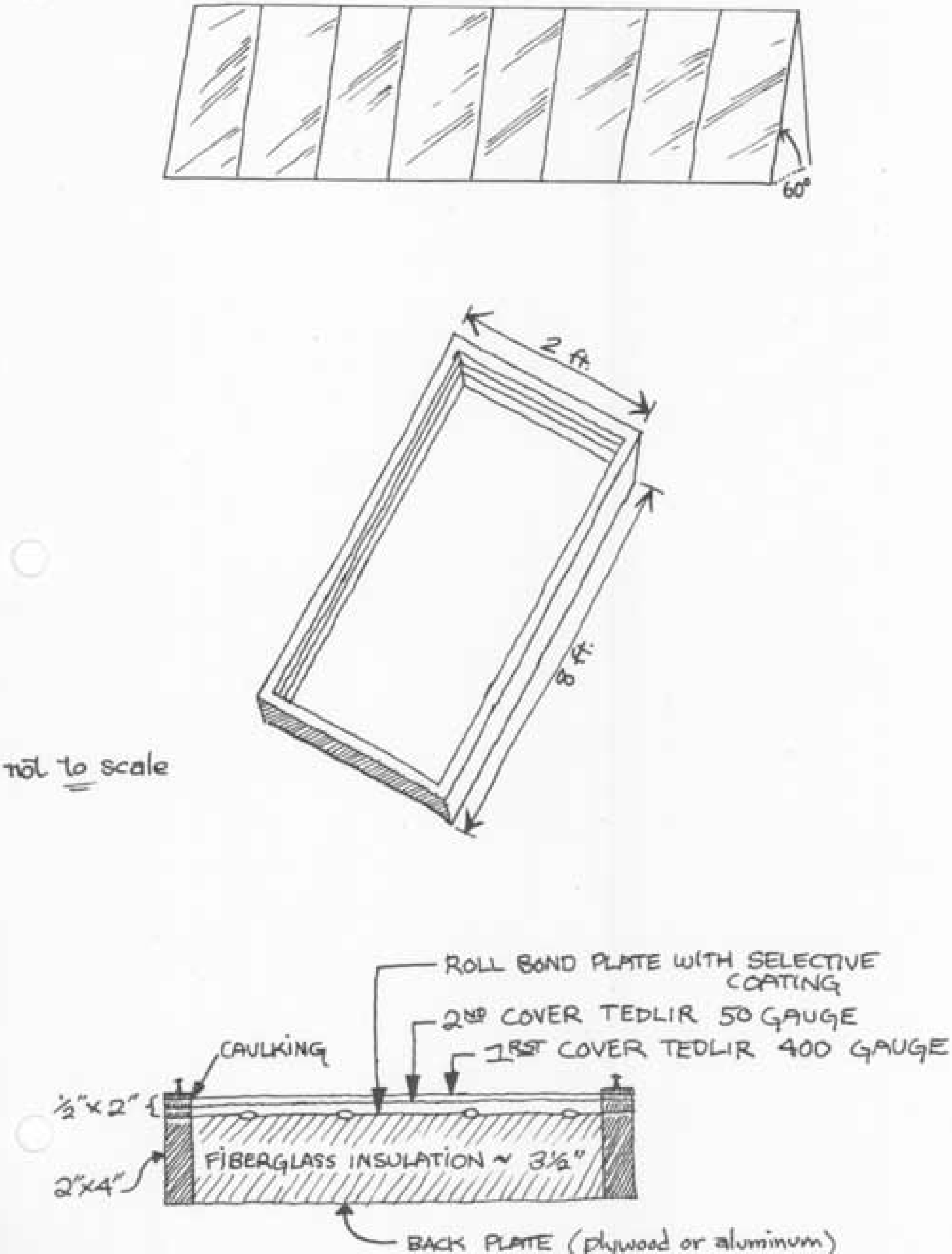


Figure 2.

Figure 3.


60°
2 ft.
8 ft.
not to scale
ROLL BOND PLATE WITH SELECTIVE COATING
2ND COVER TEDLIR 50 GAUGE
1RST COVER TEDLIR 400 GAUGE
CAULKING
½"×2"
2"×4"
FIBERGLASS INSULATION ~ 3½"
BACK PLATE (plywood or aluminum)

Heat Storage

During periods when the sun is not providing energy to the collectors (night or overcast days), a storage system will be employed to provide heat which was collected during sunny periods. The storage of heat can be implemented in a variety of ways. The most common method consists of a large tank which can hold enough heated water to meet the energy requirement for a given number of days. Crushed rock or gravel is often put in or around the tank to supplement the storage of heat in the water.

Where space is a problem, eutectic salts are used for heat storage. A eutectic salt is a material which undergoes a liquid-solid phase change within the temperature range required for storage. The phase change requires a much greater amount of energy for a given change in temperature than does the same substance without changing phase. For example, it takes approximately 80 calories of energy to raise the temperature of one gram of ice one degree at the starting temperature of 0° C. After the temperature change, the ice will have changed phases and will be in its liquid state. To raise the temperature of the water one more degree will will require only one calorie per gram. A eutectic salt suitable for use in the solar collector storage system should have a melting point somewhere between 120 and 180° F. Thus, the eutectic salts require less volume for a given storage capacity than water. Since the college does not have a space problem and since the cost of eutectic salts is somewhat high, the heat storage will not employ eutectic salts.

Heat storage will be primarily in water. The possibility of using gravel for additional storage is an engineering problem not dealt with here. It will be assumed that water will be kept in an underground tank with loose-fill insulation around it. The optimum time which should be allowed for heat storage could not be calculated due to lack of information. Subject to revision, the system will be designed to hold enough heat to satisfy one day of heating requirement in the month of January. This would require a tank of 100,000 gallons capacity.

There is another possibility for heat storage which should be investigated. It consists of gathering heat in the summer months and pumping it into a confined aquifer in the underlying bedrock. The heat would then be used in the winter months. The feasibility of this system depends upon the geologic structure of the area (5). Marlboro College does not have the facilities to carry out such an investigation; however, a study in progress of the township of Marlboro may yield the required information.

Computer Analysis of the Collector System

The analysis was performed using the equations given by Liu and Jordan (6) for intensity of radiation and by Whillier (7) for collector performance. All calculations were made specifically for Marlboro College at a latitude of 42°85' and a New England climate. However, many of the results are generally applicable for the New England area.

The computer used for the calculations was a Hewlett-Packard Model 9820A with a Math I ROM, a peripheral control ROM and a plotter.

Optimization of Tilt Angle

Since the tilt of the collector is not greatly dependent on diffuse radiation, optimization of tilt angle was carried out by comparing amounts of direct radiation outside the atmosphere falling upon the surface tilted at different angles for each month of the year. Equation 2 was used for these calculations. The results of this analysis are found in Figure 4. An angle of 60 degrees appears to be the optimum because of the necessity of collecting a maximum of solar insolation during the winter months.

Daily Radiation on an Inclined Surface

The radiation on the inclined plane at the surface of the earth was calculated using Equation 3, derived by Liu and Jordan (6), for hourly radiation and integrating it from sunrise to sunset for the 16th day of each month. The results are given in Table 2.

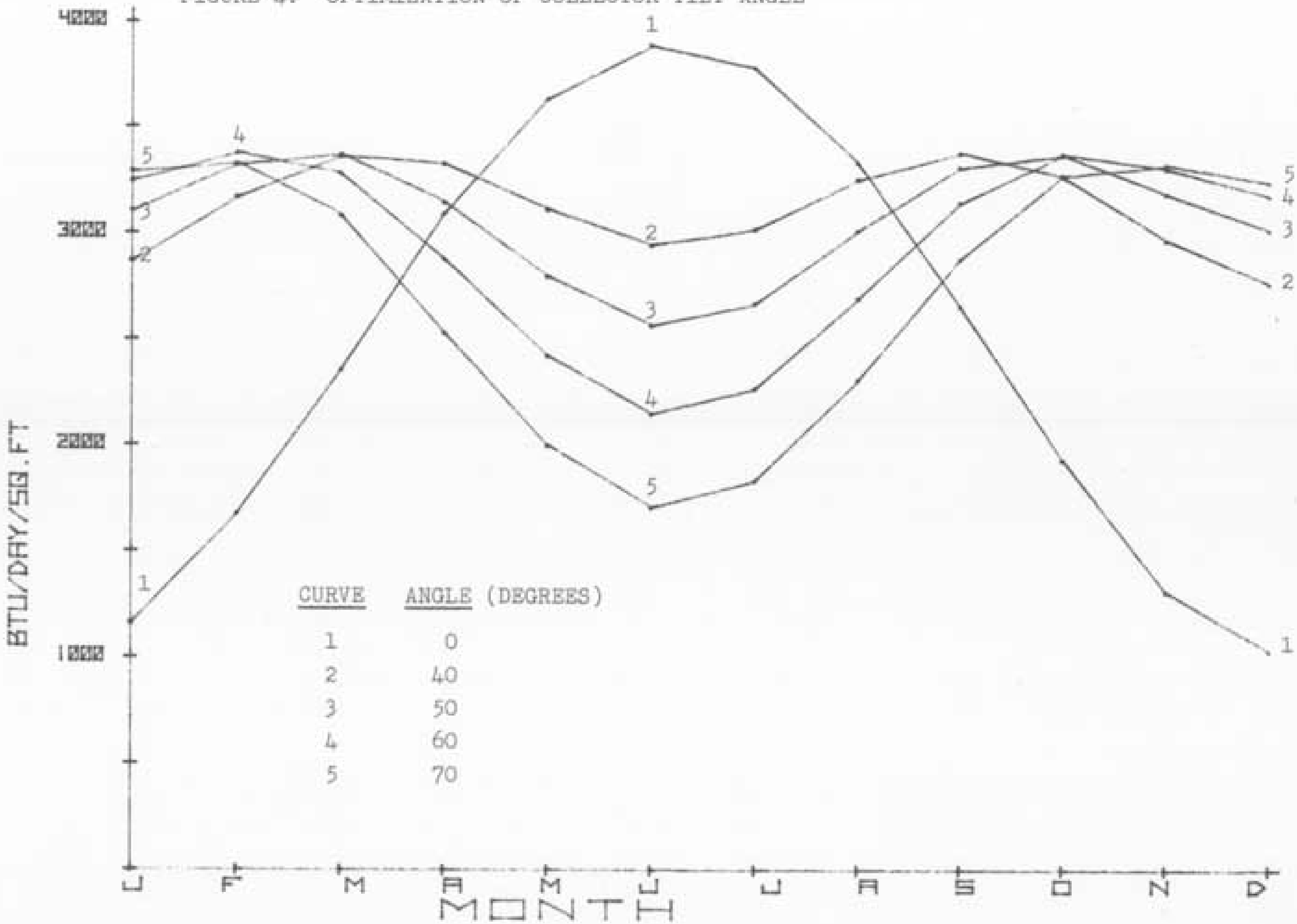
Table 2. Average Mean Daily Radiation on a Surface Tilted 60 Degrees toward the South at Marlboro, Vermont

Month	Radiation BTU/ft^2/day	Month	Radiation BTU/ft^2/day
January	1120	July	1260
February	1140	August	1270
March	1150	September	1330
April	1090	October	1220
May	1120	November	1040
June	1170	December	1020

Radiation Absorbed by Collector

The equations for the absorbance are taken from the article by Whillier (7). The parameters involved in this calculation are the radiation striking the surface (see above), incident angle of the rays striking the collector, transmission characteristics of the covers, reflectivity of the covers, first order reflections between the two covers and between the second cover and the absorber plate, loss through dirt on the covers, and, finally, shading caused by the cover supports. All of these are taken into account by Equation 4. The results of radiation absorption are combined with those of thermal loss and are given in Table 3, reported under Collector Performance.

FIGURE 4. OPTIMIZATION OF COLLECTOR TILT ANGLE



Collector Heat Loss

Heat loss equations are also given by Whillier (7). The parameters are the ambient air temperature, blackbody temperature of the sky, plate temperature of the collector, temperature of the covers, wind speed, transmittance of the covers for long wavelength radiation, the fraction of long wavelength radiation absorbed at the first cover, emissivity of the cover plate for long wavelength radiation, heat loss through the back of the collector, and heat loss through the sides. The calculations yield a value for conductive, convective, and radiative heat loss from the collector. One deviation from the Whillier method was made. Rather than assume that the blackbody temperature of the sky is simply 10 degrees lower than ambient temperature, the sky temperature was calculated using Equation 5c given by H. Buchberg and J.R. Roulet (8).

The variable parameters for the results given in Figure 5 are collector temperature and emissivity in the infra-red wavelengths for the absorber plate. Note that the results for a plate with an emissivity of 0.9 show a much higher heat loss than for a plate with an emissivity of 0.06 at the corresponding temperature.

Collector Performance: Total Heat Collected

The total heat collected is simply the total heat absorbed minus the thermal heat loss with a slight modification by the heat exchanger efficiency (90%). Results for different solar collector temperatures and emissivities are included in Table 3.

The collector efficiencies can now be calculated. The efficiency for a given month is equal to total heat collected divided by total heat incident at the collector surface. The efficiency of the collector at various temperatures and emissivities is presented in Figure 6. It can now be seen that a selective surface is essential for maintaining suitable efficiency at this latitude.

Cost Analysis of the Flat Plate Collector System

System Costs

For system costs, the present value of capital and operating costs are computed for 20 years, the minimum expected life of the solar collector system. In order to remain in a general form, the results are given for ranges of three different variables: size of the solar plant, cost of the solar plant (dollars/ft^2), and incremental cost of auxiliary heat above and beyond inflation (percent increase/year).

Solar Plant Costs

The major capital costs are for the solar collector panels, piping, pumps, regulatory equipment, and heat storage. Present

FIGURE 5. HEAT LOSS FROM COLLECTOR

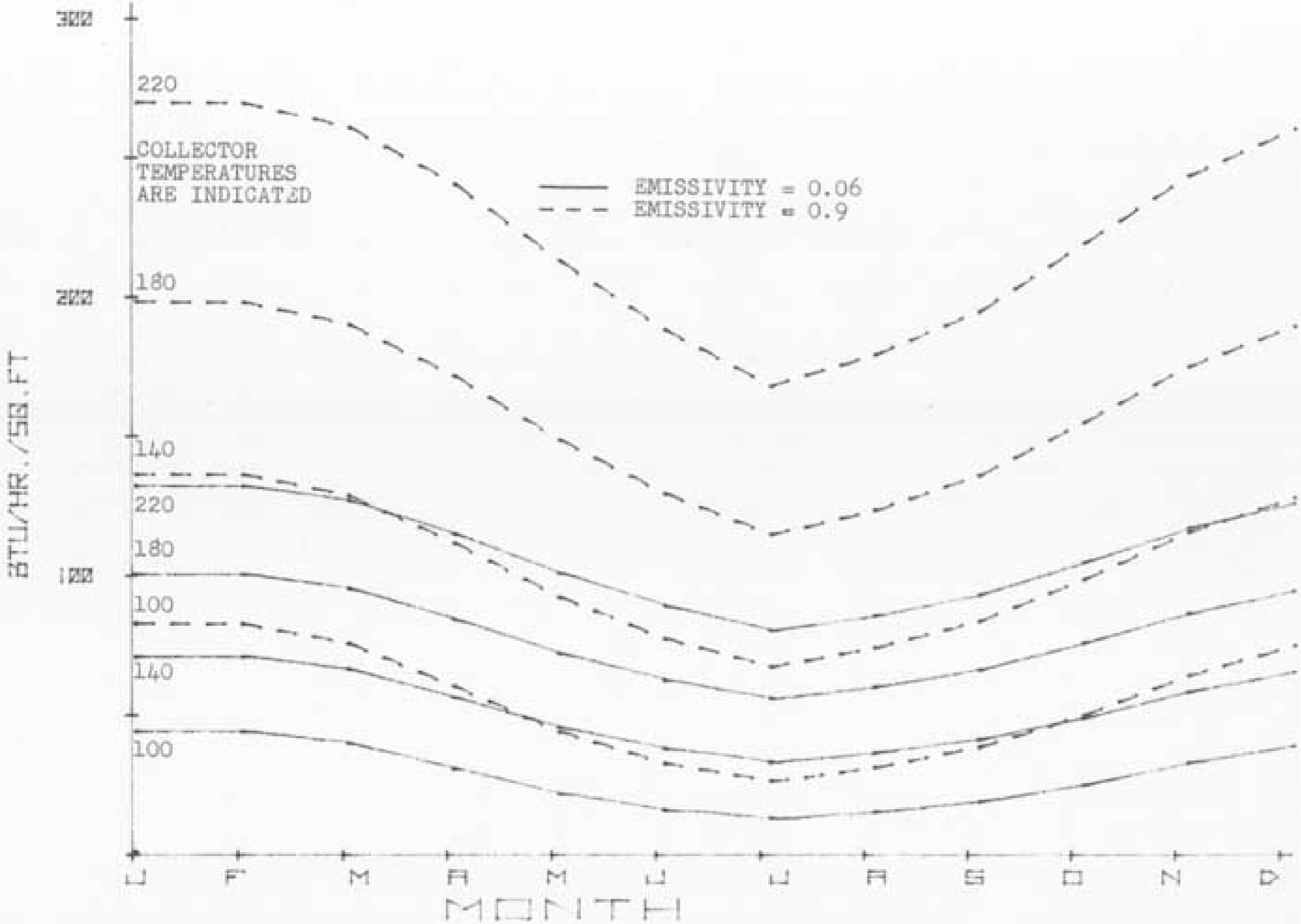


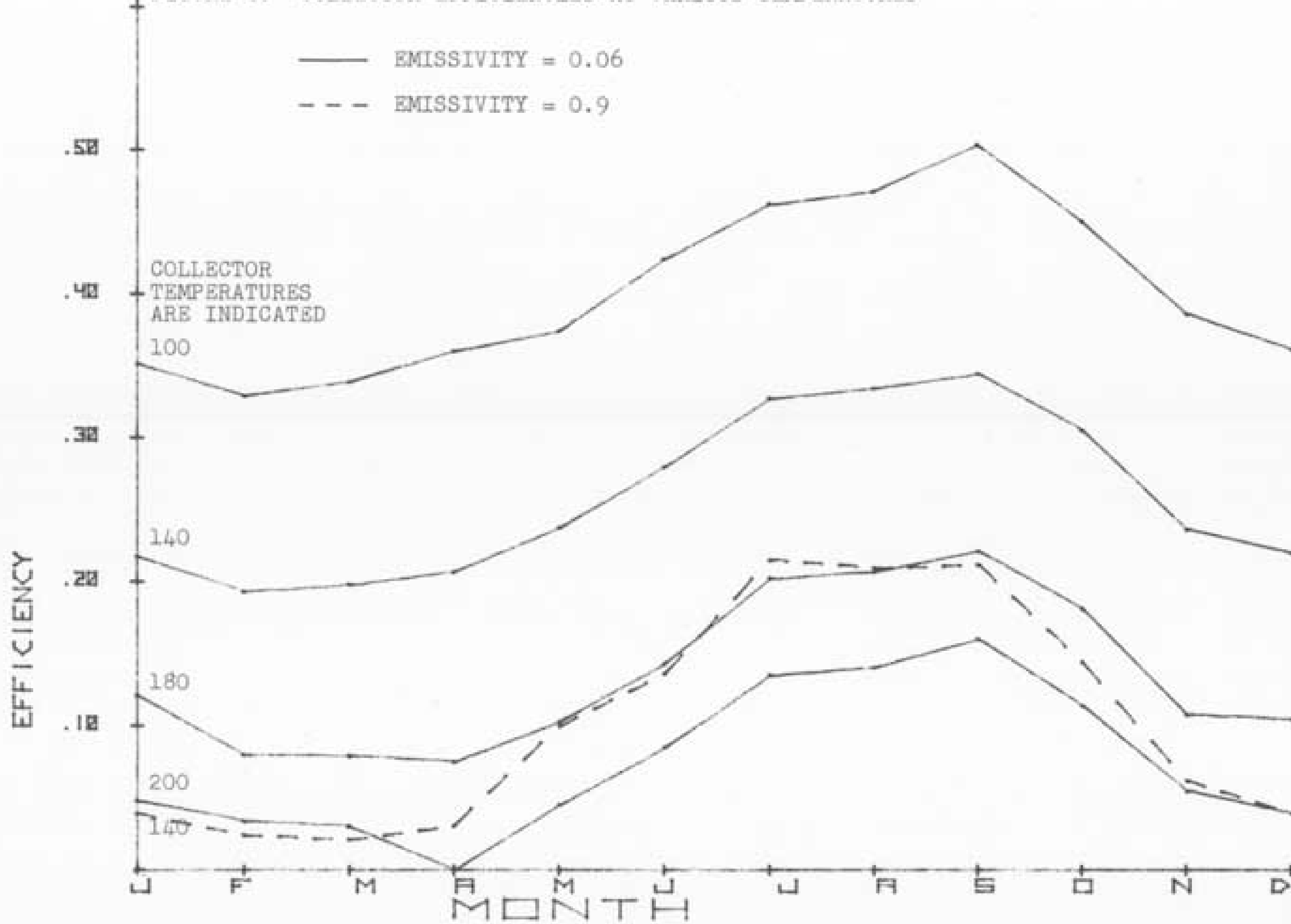
Table 3. Total Heat Collected on Flat Plate Collectors Tilted 60 Degrees with an Absorptivity of 0.90 at Marlboro, Vermont

All Values are Average Radiation Absorbed in BTU/ft^2/day

Temperature*:	100	140	140	180	200
Emissivity :	0.06	0.06	0.95	0.06	0.06
January	392	239	28	119	46
February	375	206	16	73	22
March	382	207	14	69	19
April	378	198	18	59	0
May	429	251	80	98	35
June	489	304	132	139	67
July	573	385	226	212	142
August	594	404	228	225	154
September	668	445	251	263	190
October	549	370	164	208	130
November	395	233	38	92	47
December	368	223	26	95	35

* Temperature of collector surface in degrees Fahrenheit.

FIGURE 6. COLLECTOR EFFICIENCIES AT VARIOUS TEMPERATURES



value of all these items is the purchase cost. In the cost curves (Figures 7 - 16) the collector costs vary from \$1.00 to \$10.00/ft^2. The reason for this range is seen in Table 4, where various estimates of solar heating equipment costs are listed. The large cost range for solar heating systems is primarily due to the high potential, but as yet unexplored market for solar collectors. There is not yet a large-scale production of solar collector systems.

Alternatively, the college could construct its own solar collectors due to the inherent simplicity of equipment design. Local labor could be used or, possibly, students could be hired on a work-scholarship basis to build the collectors. Referring to Table 4, the most probable costs for solar equipment if constructed by the college would be the following:

Table 5. Probable Cost of Solar Collector System if Constructed by Marlboro College

Materials	\$/ft^2
Wood (support members)	0.12
Insulation	0.10
Roll-bond absorber plate	1.00
Selective coating	0.35
Tedlar (10 year replacement)	0.33
Total: collector materials	1.90
Other system costs	
Piping	0.14
Pumps	0.20
Heat exchangers	0.15
Labor and miscellaneous	1.00
Total: system cost	3.39

Added to the cost of the solar collectors is the capital cost of the heat storage system. As mentioned before, the system will have a minimum storage capacity of 840,000 lb of water (100,000 gallons). At \$0.05/lb (Table 4), this is \$42,000 added to the cost of the collectors to give the total cost of the sqlar energy heating system.

FIGURE 7. SYSTEM COSTS

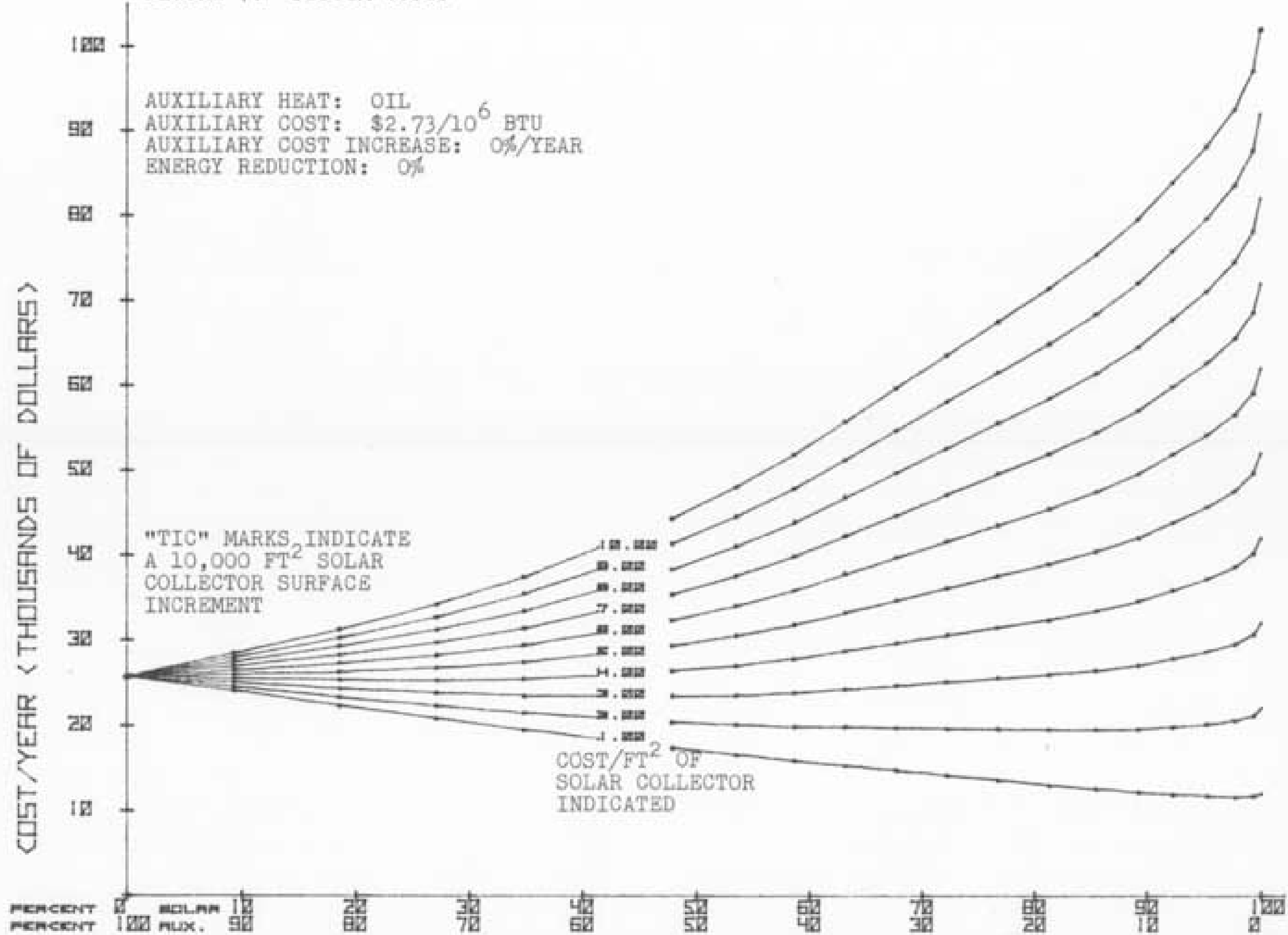


FIGURE 8. SYSTEM COSTS

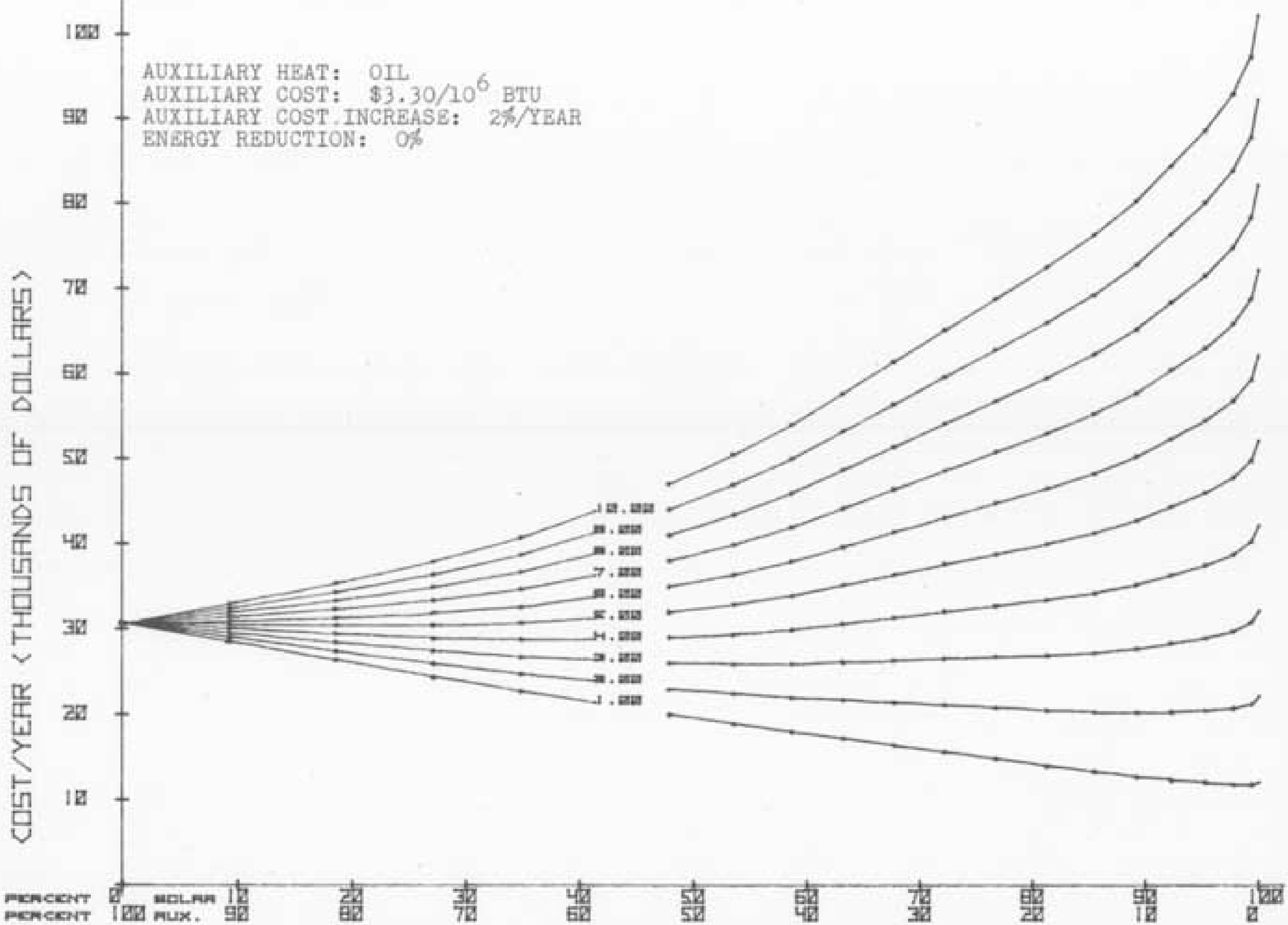


FIGURE 9. SYSTEM COSTS

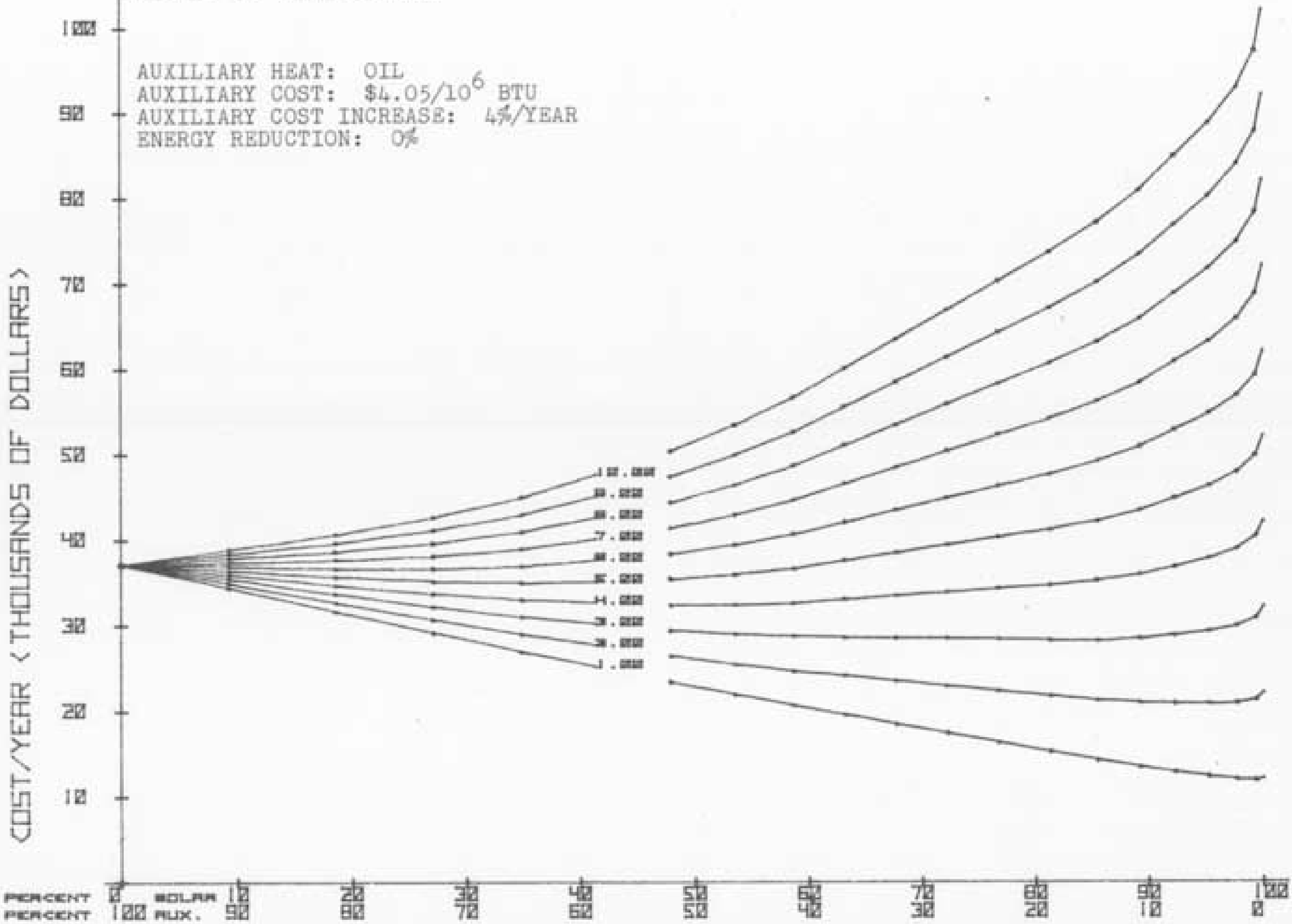


FIGURE 10: SYSTEM COSTS

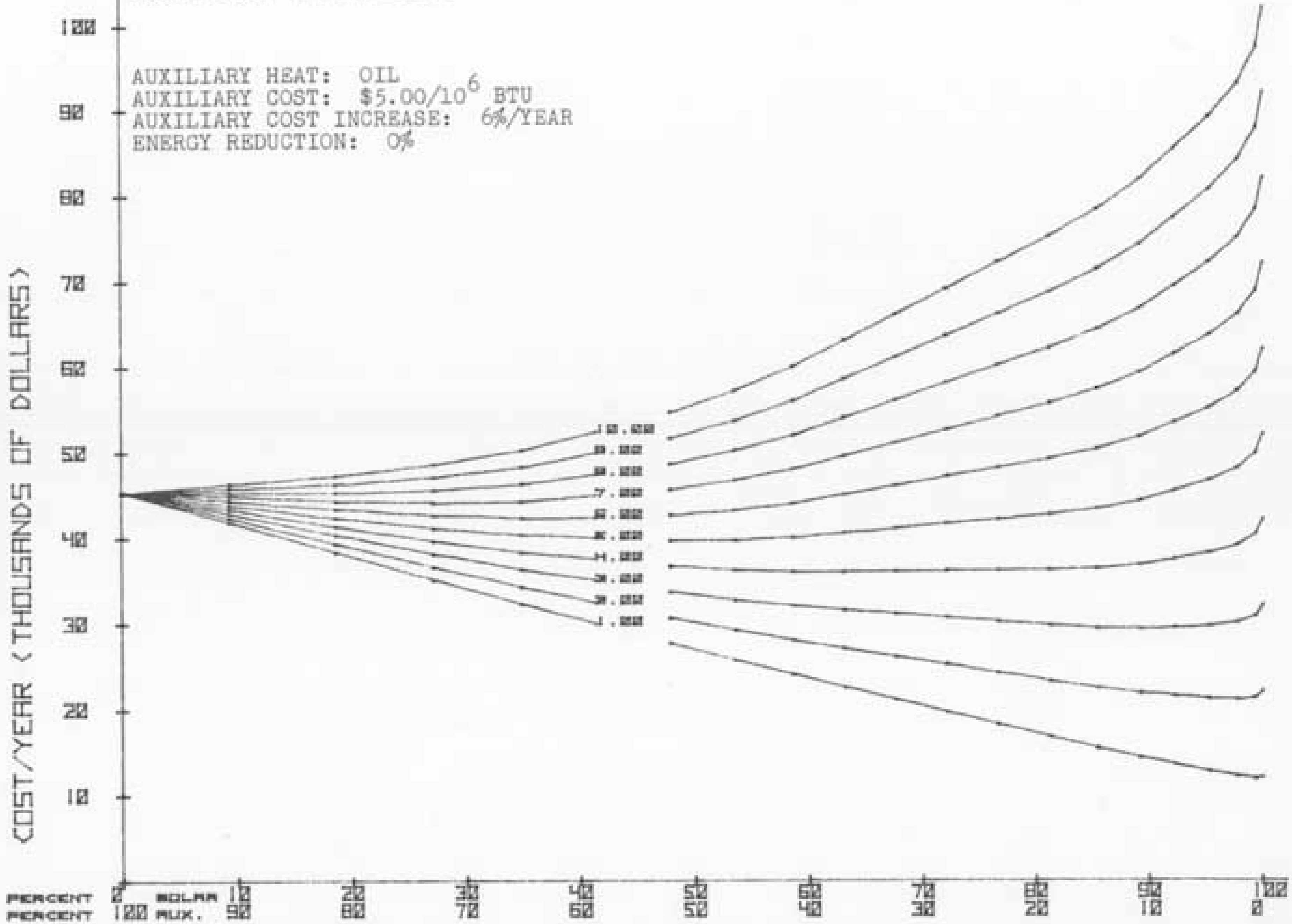


FIGURE 11. SYSTEM COSTS

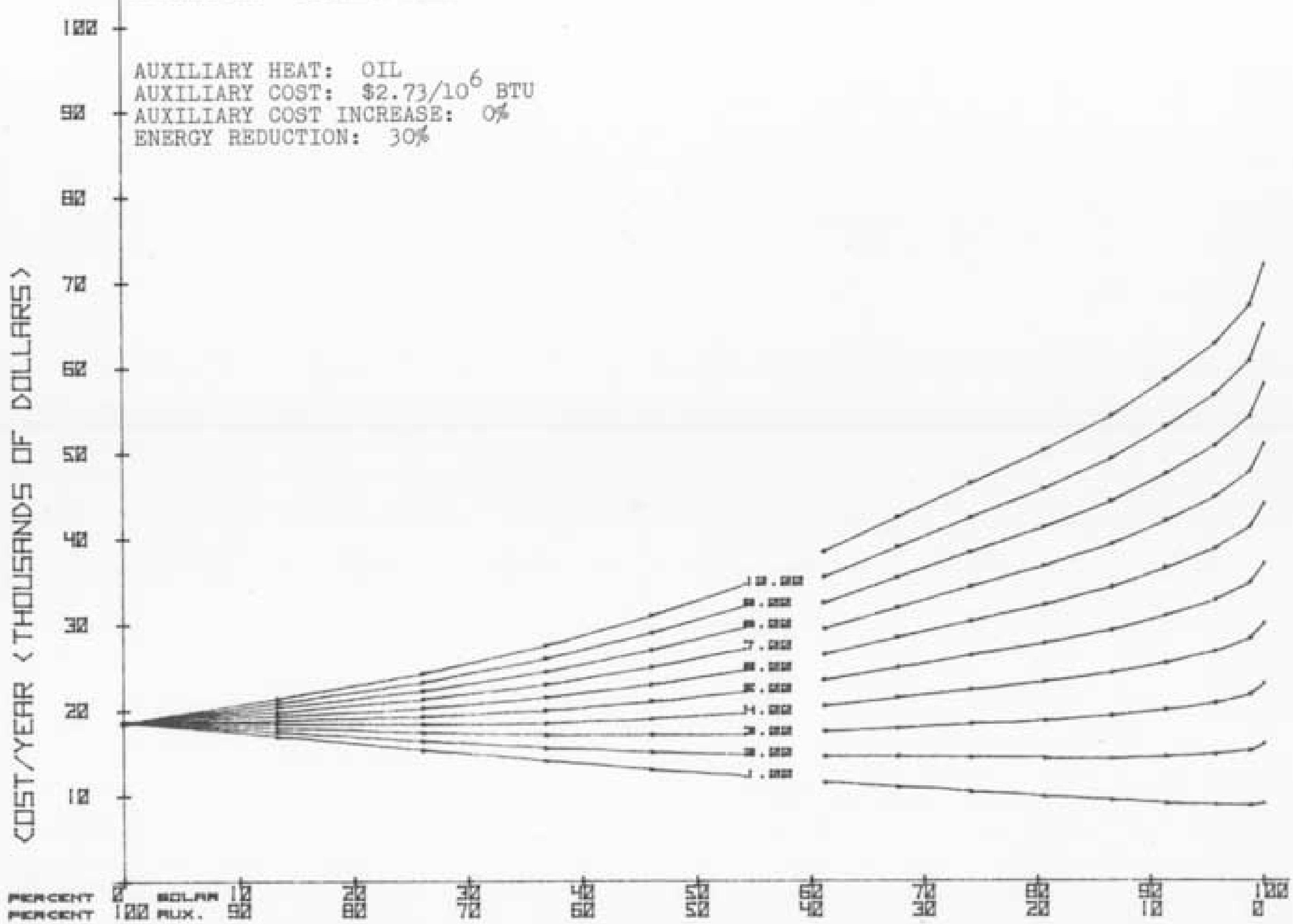


FIGURE 12. SYSTEM COSTS

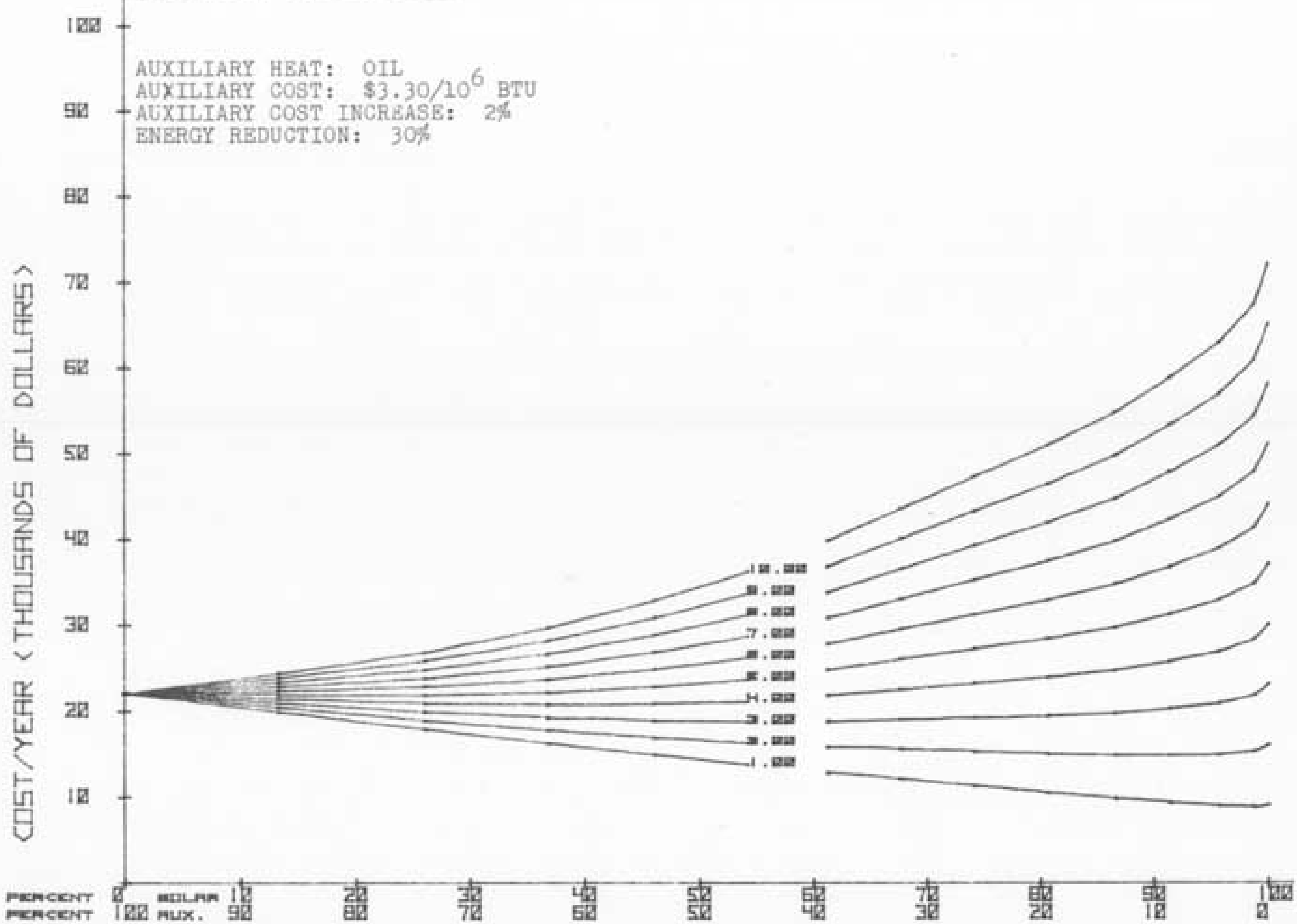


FIGURE 13. SYSTEM COSTS

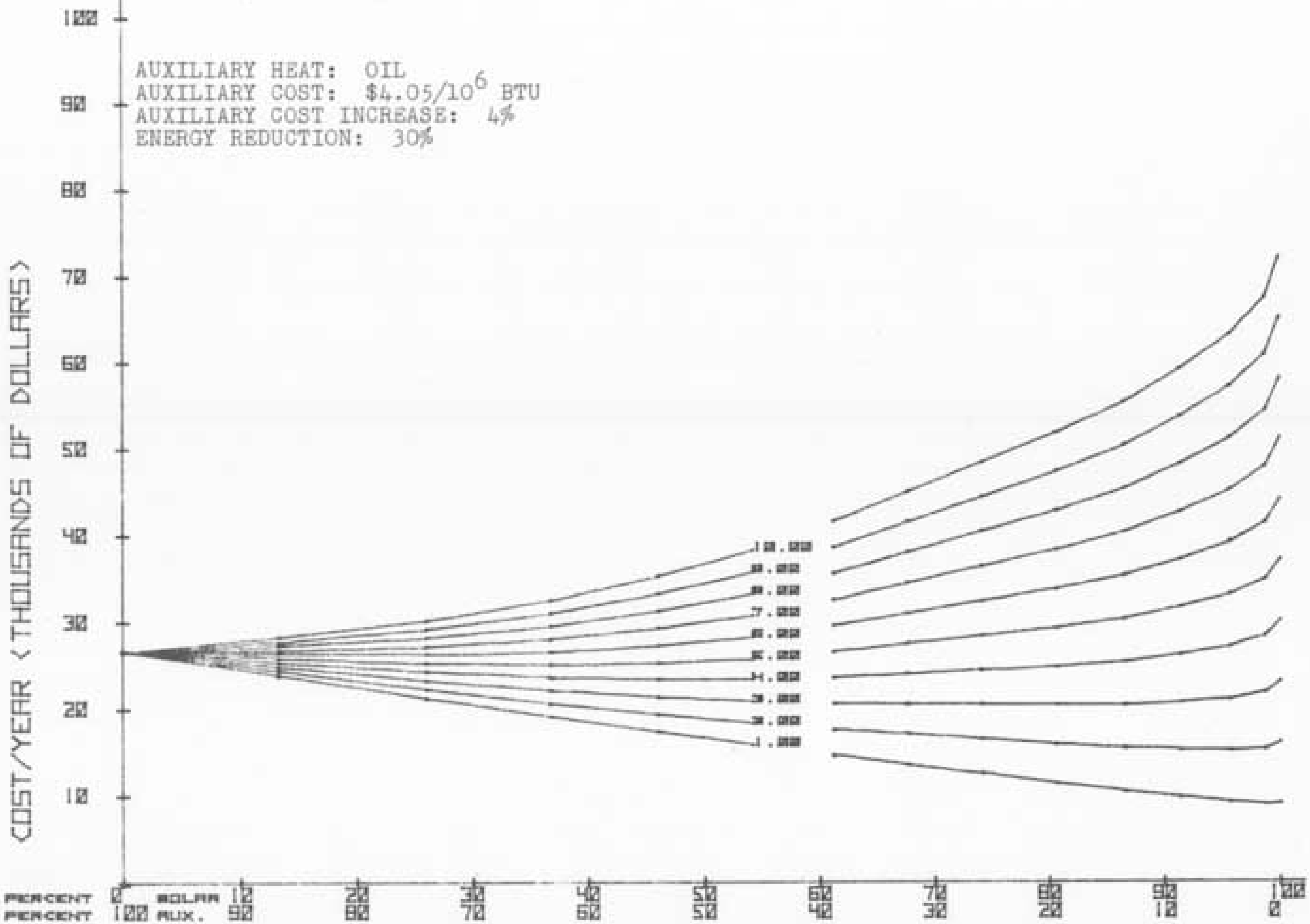


FIGURE 14. SYSTEM COSTS

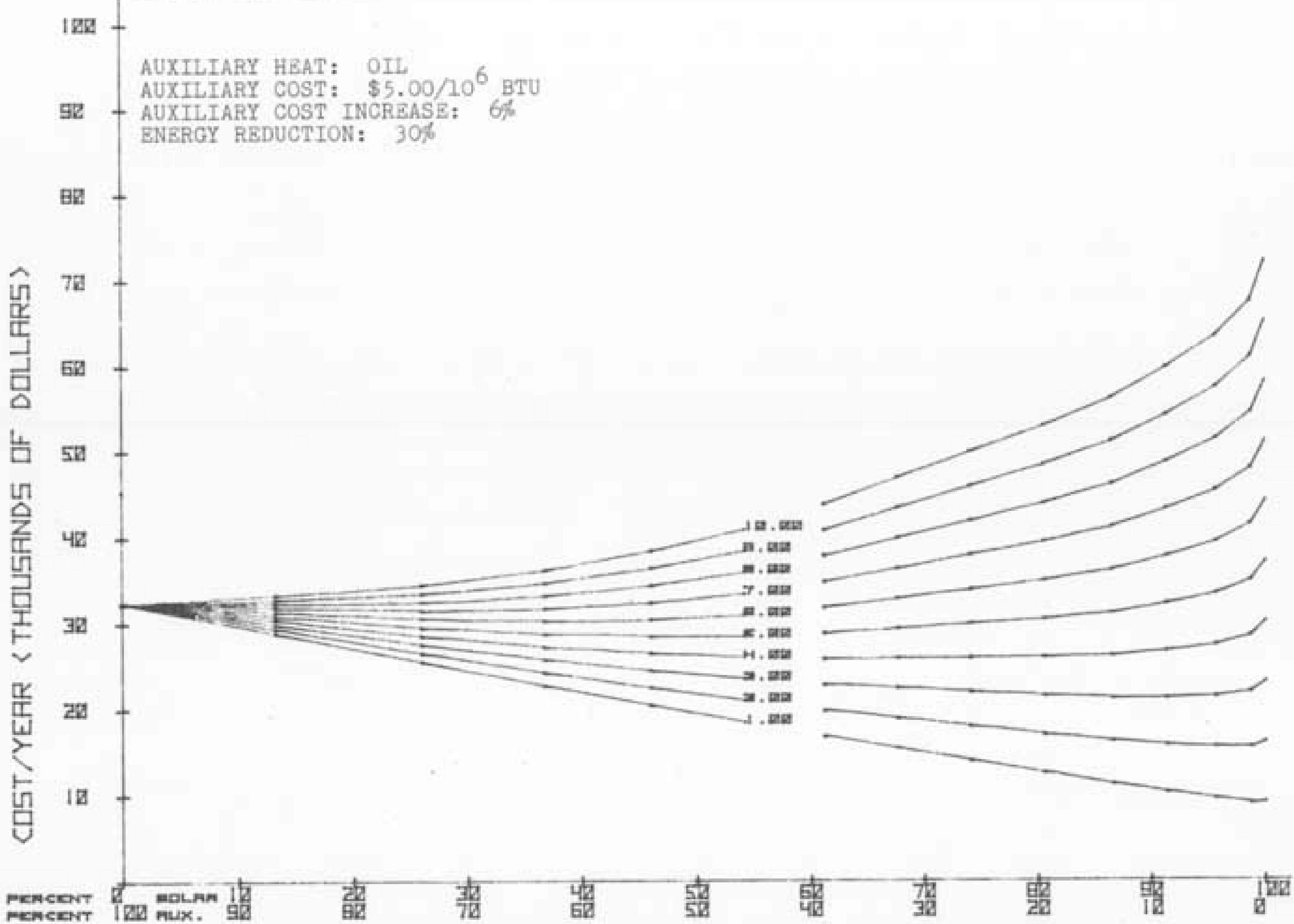


FIGURE 15. SYSTEM COSTS

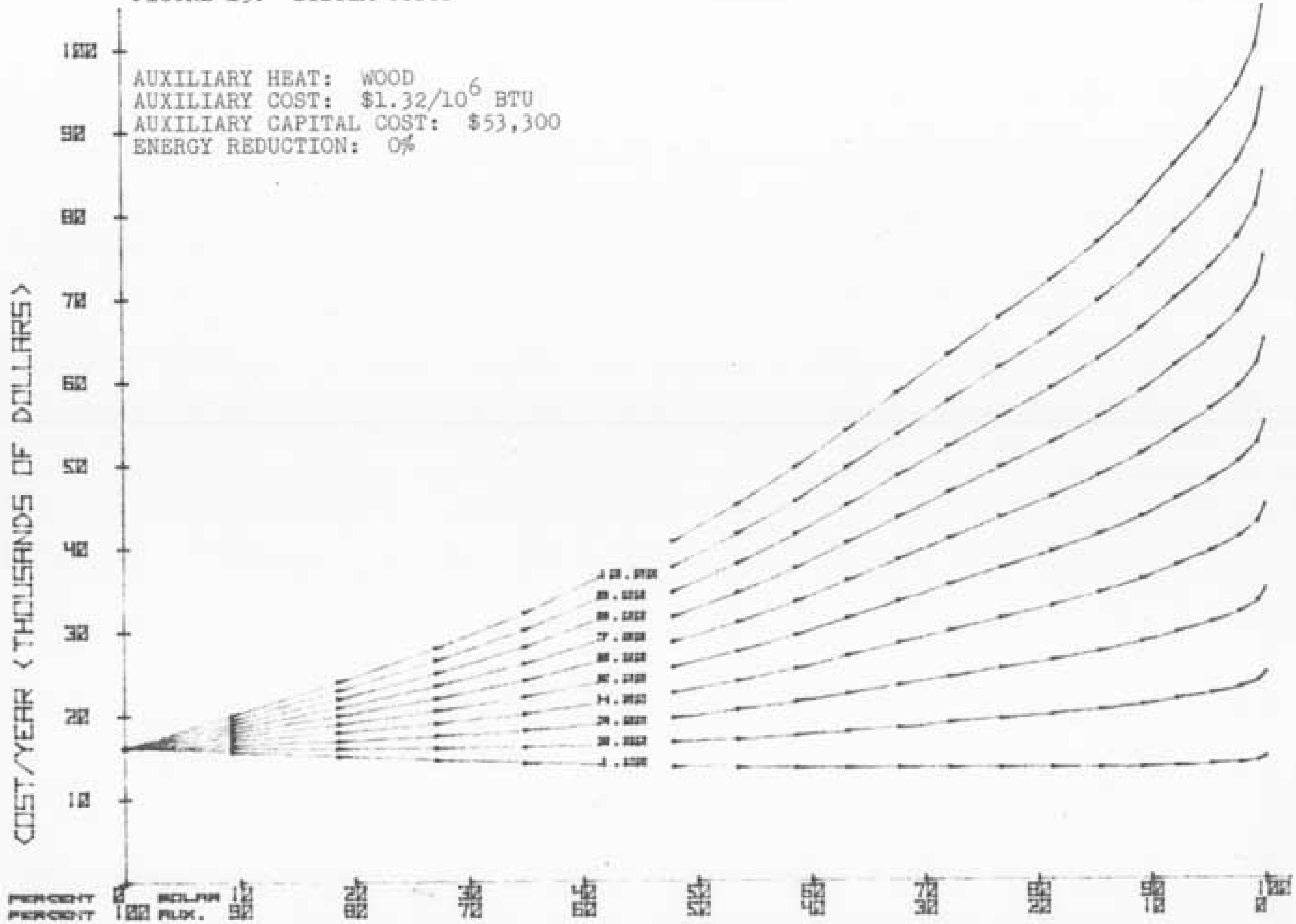


FIGURE 16. SYSTEM COSTS

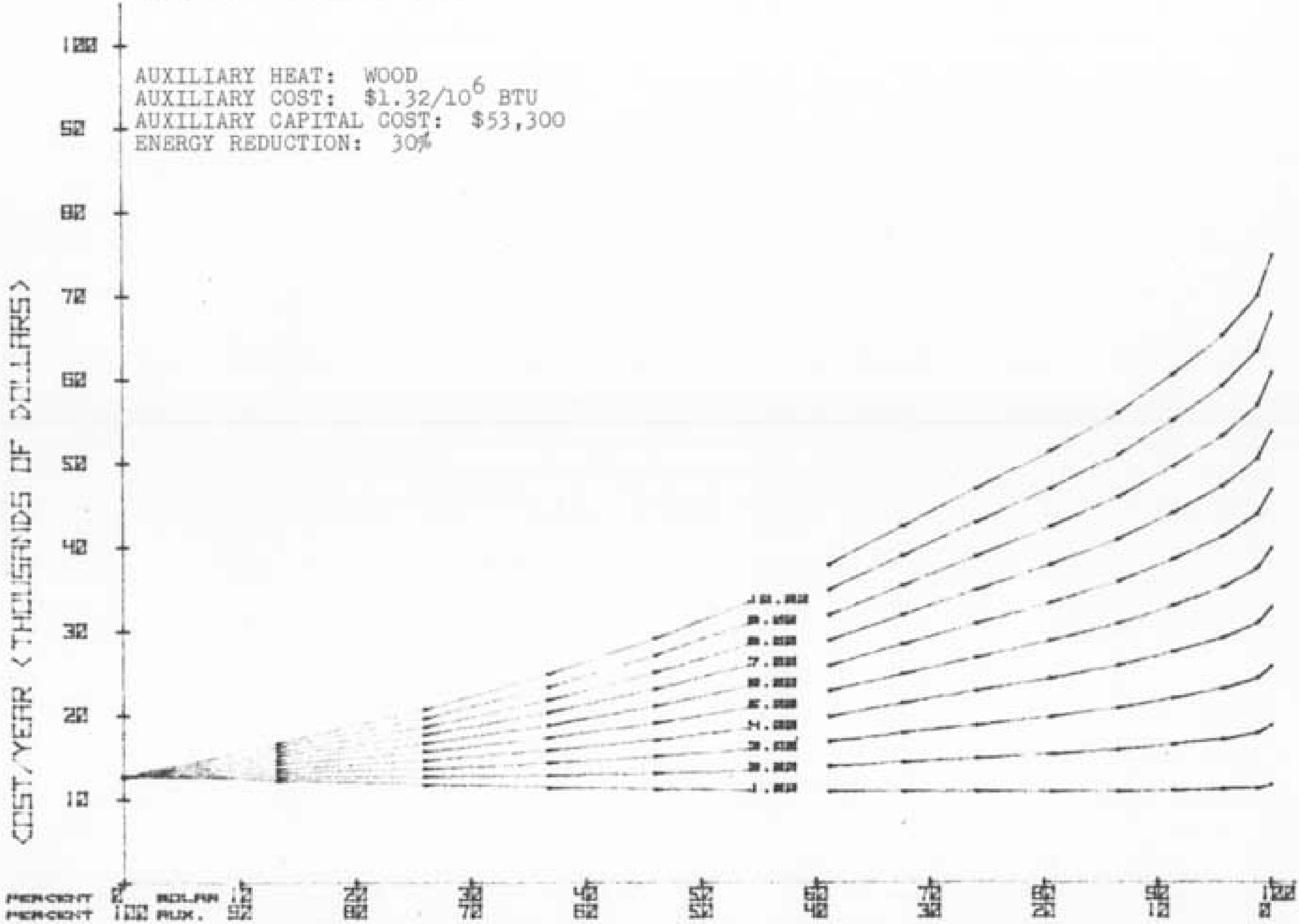


Table 4. Material Costs for Solar Heating System Components

Flat Plate Collectors (assume twenty year life)	
Lockheed-NASA (9)	$1.00/ft^2$
Eibling (10) (materials only)	1.15 to $1.90/ft^2$
Boer (11) (with CdS-Cu_2S cells)	$2.95/ft^2$
(without cells)	$1.80/ft^2$
Sunworks, Inc.	$10.42/ft^2$
Environmental Energies	$3.00/ft^2$
PPG Industries	6.00 to $7.00/ft^2$
Absorber Plate Only	
Olin Brass Company	$1.56/ft^2$
Trantor-Platecoil Division	$8.10/ft^2$
Total Flat Plate Collector Systems	
Löf (12)	$5.95 to $7.90/ft^2$
Heat Storage (Sensible-H_2O)	
Sandia Labs (13)	$0.075/lb
Lockheed-NASA (9)	0.05/BTU
Löf (12)	0.05/lb
Heat Storage (Intrinsic-Salts)	
Sandia Labs (13)	$0.50 to 1.00/lb
Fluid Transmission, Distribution, and Controls	
Sandia Labs (13)	$0.143/ft^2$ of heated area
Löf (12): Pipes	100 + $0.10/ft^2$ of collector
Pumps	50 + $0.20/ft^2$ of collector
Heat Exchangers	75 + $0.15/ft^2$ of collector
Controls	150
Miscellaneous	
Lumber (rough cut)	$0.12/bd ft
Insulation (fiberglass): 3½"	$0.095/ft^2$
6½"	$0.175/ft^2$
Tedlar (DuPont): 400 gauge	$0.1357/ft^2$
100 gauge	$0.0339/ft^2$

Auxiliary System Costs

An auxiliary system is any system which can supply heat on demand. This includes gas, oil, coal, wood, or any other fuel-fired heating plant. At the college, the present oil heating system could be used as an auxiliary heat source. The cost of running the oil system has been calculated and includes only operating costs. The fact that a major portion of the oil heating system will have to be replaced in the next twenty years has been ignored. But it should be recognized that this cost would raise the present value cost of the oil heat. Maintenance costs for all systems (solar, oil, and wood) are estimated to be equal and have been left out of the calculations.

The present value of future oil payments is calculated by use of the relation,

$$PV_{oil} = C + \frac{C[1+r][1+I]}{[1+i]} + \frac{C[1+r]^2[1+I]^2}{[1+i]^2} + \frac{C[1+r]^3[1+I]^3}{[1+i]^3} + \cdots + \frac{C[1+r]^{19}[1+I]^{19}}{[1+i]^{19}} \qquad (6a)$$

where, C = present cost of oil per year

r = rate of price increase above and beyond inflation

I = rate of inflation

i = interest rate on invested capital

If it is assumed on the average that the rate of inflation will be approximately equal to the rate of interest, then the quantities 1+I and 1+i cancel out of each term in Equation 6a. This equation then simplifies to,

$$PV_{oil} = C + C[1+r] + C[1+r]^2 + C[1+r]^3 + \cdots + C[1+r]^{19} \qquad (6b)$$

factoring out the C,

$$PV_{oil} = C[1 + (1+r) + (1+r)^2 + (1+r)^3 + \cdots + (1+r)^{19}] \qquad (6c)$$

The geometric series in the brackets can be reduced to,

$$\frac{(1+r)^{20} - 1}{r}$$

This gives,

$$PV_{oil} = \frac{C[(1+r)^{20} - 1]}{r} \qquad (6d)$$

to find the average cost of oil per year, divide by 20,

$$PV_{oil} \text{ (average cost/year)} = \frac{C[(1+r)^{20} - 1]}{20r} \qquad (6e)$$

Figures 7 through 14 show the yearly cost of different solar-oil systems for values of r equal to 0, 2, 4, and 6 percent. Figures 7 through 10 contain curves which do not take into account any reduction in the college heating requirement, and Figures 11 through 14 reflect a 30 percent heating reduction through conservation methods.

In each of these figures, the ordinate is the cost per year of providing 100 percent of the heat with the appropriate percentages of oil and solar systems as found on the abscissa. There are ten curves in each figure to account for the uncertainty of solar collector system costs. As calculated in Table 5, with a collector system cost of $\$3.39/ft^2$, the predicted cost of building the solar heating system would be just above the "3.00" curve in each figure. For example, using this assumption, in Figure 7 the cost of a 70 percent solar-30 percent oil heating system would be approximately the same as a 100 percent oil heating system, or $26,000/year. The cost of oil heat was calculated using Equation 6e, where C equals the present yearly cost of oil.

On each of the curves in Figures 7 through 14, it should be pointed out that each of the "tic" marks represents a 10,000 ft^2 increase in solar collector surface area. Notice that in Figures 7 through 10 to provide 100 percent solar heat would require nearly 200,000 ft^2 of solar collector surface, whereas after a 30 percent reduction in heat requirement (Figures 11 through 14) only 130,000 ft^2 is necessary. As pointed out earlier in this section, the amount of collector surface is subject to some uncertainty due to a lack of adequate solar insolation data.

The cost of a wood-fueled auxiliary system includes the initial capital cost of the furnaces plus the present value of wood for twenty years (see the section on wood energy). The cost of the furnaces is divided by the twenty years of their expected lifetime to find a yearly cost. Since the price of wood consists primarily of labor costs, there should be no increases above and beyond that of inflation. Figures 15 and 16 show costs for varying wood-solar systems. Once again, a possible 30 percent reduction in energy use is taken into account. It should be noted in these figures that wood heat is significantly cheaper than either oil or solar heat unless the solar system costs less than $\$2.00/ft^2$.

Conclusions

College-owned land can now supply enough wood to provide 28 percent of present energy needs or 42 percent if that need is reduced by 30 percent through conservation. On the assumption that the college will make that reduction, Figure 16 shows that the cost for a wood-solar heating system would be $18,000 per year at a solar system cost of $\$3.39/ft^2$ of collector. That figure can be compared to the cost of oil heat. As an example, if it is assumed that oil will increase in price at a rate of 4 percent per year (cost per year given on the ordinate of Figure 13), a figure of $27,000 per year results. Thus, the solar-wood heating system would save the college 120,000 present value dollars over its 20 year expected minimum life. This figure would be augmented by any oil heating system replacement costs during that time period.

Although predictions of future oil prices are just guesses, the figure of 4 percent oil price increase per year appears conservative, at least for now. This figure was chosen because it represents a doubling of the price of oil over the 20 year time period in question, probably not an altogether unreasonable assumption. But it should be pointed out that the only reason for providing all of the Figures 7 through 16 is that there is an uncertainty over future oil prices. Indeed, that uncertainty extends also to the availability of that oil. It is well known that educational institutions such as Marlboro College will probably be among the first to do without oil should tight supplies lead to rationing.

Finally, it is recommended that the college carry out further research in two areas before implementing a full-scale solar-wood heating system. First, more information needs to be obtained on the amount of solar insolation available at the college. And second, a small-scale, wood-solar demonstration project should be designed and built to gain familiarity with construction and performance of a wood-solar heating system.

VI THE MARLBORO COLLEGE FOREST AS AN ENERGY RESOURCE

The major part of the summer's work was in preparation for and carrying out an inventory of the forested properties of Marlboro College.

The Forest Inventory

The attached map (Figure 17) is of the main property, two smaller pieces separate from the main campus, and the lands adjoining college property. The two smaller properties are known as the Mumford lot (adjoining the main property's eastern boundary) and the Hertzberg lot (approximately ½ mile to the east of the main property and on the south side of South Road).

The areas in which the inventory was conducted, hereafter called compartments, are shaded, and other features and landmarks of the college properties are indicated. The forest inventory was adapted from the Forest Inventory Summary System, developed for the Vermont Department of Forests and Parks, agency of Environmental Conservation by A. Patunoff, programming consultant for that agency.

Compartments

Compartment 1 is the largest and consists of 108 acres. The forest vegetation is made up roughly of 65% coniferous and 35% deciduous trees. The ages of the trees in this compartment are very mixed, but the trees are generally older than those of either of the other compartments. Most of them are over 100 years old, while some of the large sugar maples predate Vermont's accession to the Union. Compartment 1 was logged during the summer of 1973, and a total of 186,000 board feet were removed.

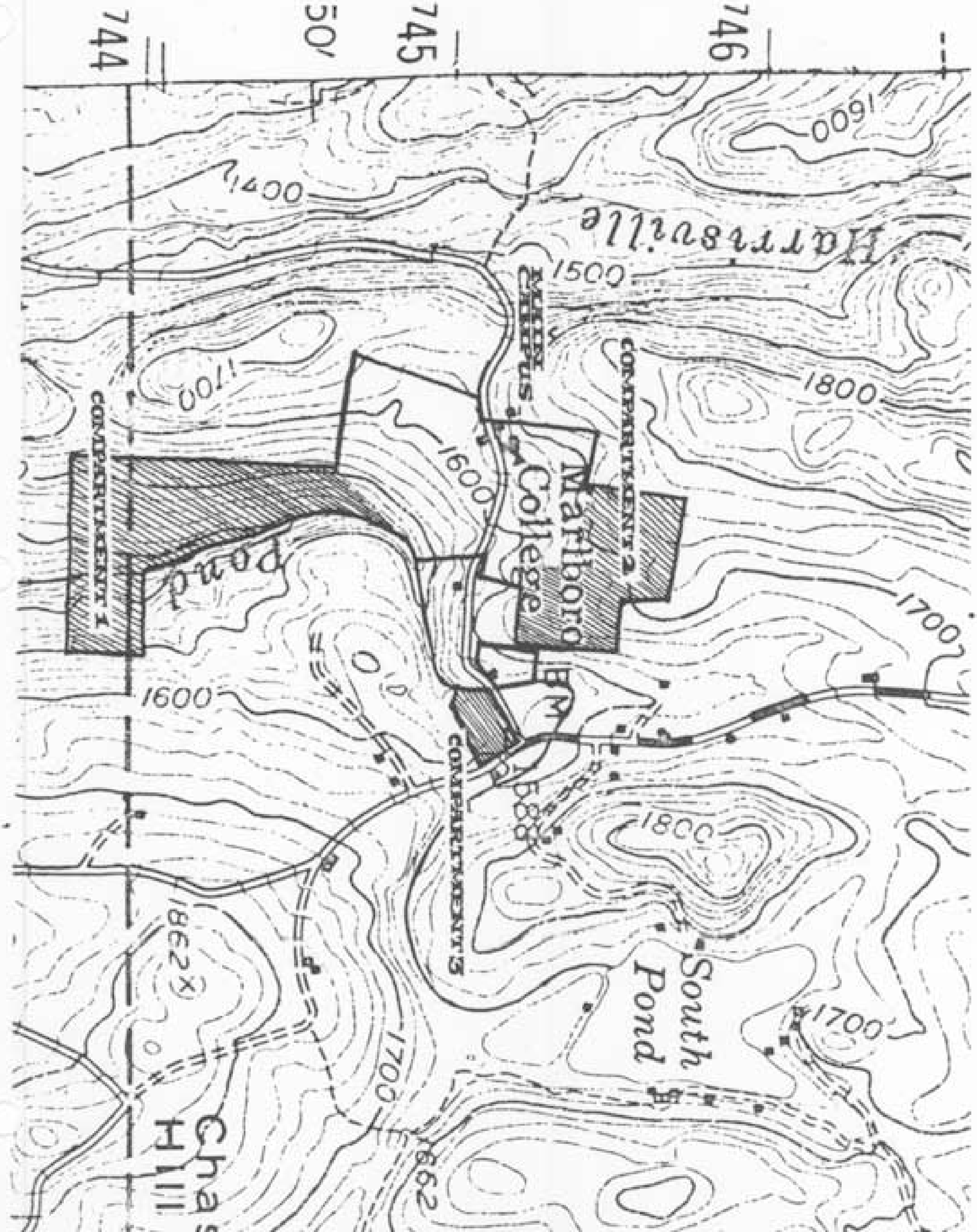
Compartment 2 contains 52 acres and is comprised mainly of hardwoods, sugar maple being the most common species. The age of this stand is approximately 60 years.

Compartment 3 consists of only 12 acres. It is 80% white pine, which are about 40 years old.

Stand Tables

Tables 6 through 8 (Appendix 2) are the stand tables for each compartment. Tables 9 through 11 (Appendix 2) present the final volume figures for each compartment. Virtually all the data contained in the inventory are presented in these six tables. An explanation of how the tables were constructed will be found in Appendix 3. It should be noted that the total yield in each of the compartments is greater than one cord per acre per year.

Figure 17.


744
50′
745
746
1400
1500
1600
1700
1800
1600
Harrisville
Main Campus
Compartment 1
Compartment 2
Compartment 3
Marlboro College
Pond
BM
1588
1800
South Pond
1700
1862
1700
Chase Hill

Wood Utilization

Before moving to a discussion of how best to utilize the forest resources of Marlboro College towards energy self-sufficiency, this use must first be justified.

It is generally known that conscientious "weeding" of a forest stimulates growth and improves the general health and vigor of the trees left standing. The crowns of the desirable trees in a properly thinned stand are able to expand and fill the gaps left by the removal of the weed trees. Thus, the photosynthetic capacity of the desirable trees is increased. A delicate balance must be maintained between the growth of the desirable trees and the creation of space in the crown cover. If too much space is maintained, sunlight will fall to the forest floor unused by trees, and growth in the stand then will not be optimal. In fact, in such cases of over-thinned stands, only little and even negative increases in growth are realized. In addition, major changes in many facets of the forest ecology occur from large amounts of sunlight falling to the forest floor.

In thinning programs the stems of the weed trees are often removed for fuel or pulp wood. Generally, the leaves, smaller branches, and roots are left in the woods. It is in those parts of trees that by far the highest percentage of nutrients are found (14). It is only logical that this be the case, since those are the parts of trees in which most of the metabolism takes place. More nutrients become available to the desirable trees then, both from decreased competition for existing nutrients and decomposition of those parts of the weed trees left in the forest. This results in greater vigor of the thinned stand.

The increased photosynthetic capacity and nutrient availability work together to produce the higher growth rate observed in properly thinned stands. In addition, the chance of disease infection and spread is decreased by the weeding out of sickly trees.

From the preceeding discussion it can be seen that the college can expect to harvest a significant amount of wood on a sustained yield basis, and with proper management it can do so with no damage and even enrichment of the ecology of its forested properties. It would be inaccurate to say that the ecology would remain unchanged. It must be remembered, however, that the college forest was severely damaged two centuries ago; indeed, the land was completely cleared and placed under tillage. The college forest has regenerated from that cleared stage and is at present in a state of successional flux. With the environmental effects of civilization as insidious as they are today, there is little doubt that an area as small as the college forest will never return to its pre-columbian state. Thus, it seems we must call our virgin forest a loss and treat our present forest as the recreational, aesthetic, and energy-producing renewable resource it is today.

It should be insisted, however, that whatever forest management program the college may adopt, any unique areas of the college forest should be preserved. The stand of huge sugar maples and hemlocks in Compartment 1 fits in this category. The total area of such preserves would not be great enough to significantly reduce the annual yield of wood.

Categories of Wood Utilization

Two broad categories of wood utilization were investigated: conventional saw-timber management and fuel-wood management. A number of particular systems were considered under the latter category, including wood-gas and methane production. At the very end of the project a very promising system emerged, combining wood and solar heat into one system, hereafter called the wood-solar system.

Saw-timber Utilization

Traditionally, forest thinning has been carried out in an effort to spur promising trees into lumber size. Very often landowners have brought the stems of the weed trees in for fuel wood. The volume removed in the weed trees, however, rarely approached the annual sustained yield of the stand. The theory is to leave as many good trees as possible for a hypothetical "timber crop" from which the landowner's heirs may someday reap great capital benefits.

If those heirs inherited a stand such as Compartment 1, and decided in 1971 to have it logged as the college did, they would have received $3800 after it was logged in 1973. That same wood, burned in a good wood furnace would have yielded roughly as much heat as 50,600 gallons or $19,200 worth of #2 heating oil at the present price of $0.38/gal (assuming equal efficiences in burning the two fuels).

Saw-Timber to Cord-Wood Conversion

$$186{,}000 \text{ BF}/500 \text{ BF/cd}^{*} = 372\text{cd}$$

Wood to Oil Heat Conversion

$$(\text{Wood: } 20\times10^{6} \text{ BTU/cd})$$
$$(\text{Oil: } 1.47\times10^{5} \text{ BTU/gal})$$

$$372\text{cd} \times 20\times10^{6} \text{ BTU/cd}/1.47\times10^{5} \text{ BTU/gal} = 50{,}600\text{gal}$$

$$50{,}600\text{gal} \times \$0.38/\text{gal} = \$19{,}200$$

In addition to the wood taken out to the saw mill, most logging operations leave large amounts of wood to rot in the forest in the form of tops, not suitable for lumber and contributing little to the nutrient cycle. Vermont county foresters use as a

*Standard conversion factor for board feet to cords, which takes into account the wood lost during milling.

rule of thumb the figure of one cord of fuel wood in the tops for every thousand board feet in the stems (15). The actual figure depends on the size of the trees in question and runs higher than one cord per thousand board feet for hardwood trees of the size common to Compartment 1 (16). So, it is safe to say that at least 186 cords were left behind in the 1973 logging operation. Using the same values and assumptions as in the previous calculation, that much wood is equivalent in heat value to 25,300 gallons of oil worth $9600. This is a total of 75,900 gallons of oil worth $28,800.

The figure of $18,800 cannot be directly compared with the $3800 received for the timber for two reasons. First, $28,800 represents the value in oil equivalents of the wood as heat. But the cost of cutting, splitting, and stacking the wood must be subtracted before this figure can be compared to the saw timber figure. From the calculations carried out later under the Wood Heat section, it is seen that this cost is $1.32 per million BTU or $27 per cord. For the 560 cords cut during the logging operation, this amounts to $15,100. This figure subtracted from $28,800 leaves a net monetary benefit to the college of $13,700, which is the figure to be compared to the value of the saw timber.

Second, the timber that was worth $3800 in 1971 would probably be worth double that today or about $7600. Thus, using the wood as a fuel would provide the college with approximately $6100 more than what could be obtained by selling it as saw timber.

There are also ecological objections to the use of the Marlboro College forest for saw timber. The harvesting methods used in logging operations are contrary to the theory behind the annual weeding type of management program outlined previously. Saw-timber operations must necessarily select the largest trees in the stand. The felling of the large boles does considerable damage to the smaller trees and saplings, the future forest. The heavy equipment and the heavy saw logs which are dragged to the yarding area cause well-documented damage to the forest floor (17). The skidding disrupts the forest floor and soil communities and alters the nutrient balance by changing the permeability, erosion, and water holding characteristics of the soil.

Finally, it is most economical to remove a great number of saw-timber sized trees at one time. Witness the 560 cords removed as saw logs and left as tops during the logging of Compartment 1, which has at present a sustained yield of only 181 cords/year. Consider then the extent of the damage caused by the felling and skidding of 186,000 board feet of saw-timber sized trees within a six week time period.

The preceeding discussion of saw-timber use will, it is hoped, dispel the seemingly popular notion that the forest is worth more to the college if managed for saw timber.

Wood as Fuel Utilization

Two conversion systems were considered: wood gasification and the incorporation of wood into a methane generating sewage treatment system.

Wood Gasification

Wood gasification is a destructive distillation process by which wood is burned in an oxygen-starved atmosphere, producing a variety of gases and other products of wood combustion. All the gases, amounting to smoke, are collected and "scrubbed" (purified), leaving a flammable mixture of approximately 61% CO, 30% H_2, and 8% CH_4. The wood gas can be stored or used immediately in much the same way as natural gas or petroleum. The gas does, however, have less energy on a weight basis than conventional fossil fuels.

Using wood gas was eliminated early in the project, primarily because commercial wood gas plants are no longer available. Nor could any design or construction information be found on the college's scale. (There are numerous plans and articles about small home-made type generators, stemming from the war years.) There is a general lack of current information of a technical nature on the wood gasification process; thus, there is need for experimentation on this process.

Anaerobic Digestion

Conversion of wood to methane by anaerobic digestion is thoroughly covered in the Organic Waste section. Briefly, however, the scheme would be to introduce wood in some form to the methane producing sewage treatment plant to augment methane production in that system. It is felt that virtually all the energy contained in the wood material could be extracted.

As the use of wood in sewage plants is a highly unconventional process, the work on this aspect of the system, like the research on wood gas, was severely hampered by a lack of technical data. An adequate evaluation of the system would depend on a large amount of experimental work. For instance, it is known that different species of wood will behave differently in the digester of the sewage plant, some not digesting at all. No data could be found, however, related to the species composition of the college forest.

The system suffers on economic grounds as well. For example, it seems that wood will require considerable pretreatment of one sort or another (an undetermined element in itself). One such process would involve reducing the wood to a powder of 30 mesh size. Capital costs of the equipment necessary to accomplish the pulverizing would exceed $100,000. In addition, the power consumption of the 50 hp and 75 hp electric motors required by the grinding equipment would be counter-productive in an energy self-sufficient system.

Wood Heat

Harvesting wood for fuel, unlike harvesting for lumber, can be carried out in complete accordance with the annual weeding type of forest management program, whose merits were presented previously. This is so primarily because of the freedom there is in selecting trees to be cut from the stand. The freedom arises from the fact that a wide range of tree sizes are suitable for fuel wood (roughly from 4 in to 20 in). Thus, a thinning program can proceed with the best interests of the forest in mind, i.e., proper balance of growth and space and removal of sickly trees.

Fuel-wood harvesting will damage the forest far less than will even the most carefully conducted saw-timber harvest. As can be seen in the "present volume" column of the stand tables (Tables 6-8), for every compartment a larger volume of wood is found in the form of trees less than saw-timber size (12 inches) than in those with diameters greater than 12 inches. It is also among the smaller diameters that the greatest growth rate is observed, and the most crowding occurs (18). For these reasons, if an annual thinning program is adopted, there will be a propensity toward smaller trees in the harvest. This means that damage to saplings and small trees during felling will be minimized. Since fuel wood will be needed in lengths of only 4 feet or less, heavy equipment and skidding of logs will not be necessary, so damage on the forest floor will also be minimized. Finally, since fuel-wood harvesting must be carried out on a yearly basis, thinning will be gradual, an important element in a good thinning program.

Amount of Wood Available

The details of the entire heating system proposed for Marlboro College by this project are presented in the Solar Energy section. Only that part of the system referred to in that report as the "auxiliary heating system" will be discussed here. The discussion will be further confined to the use of wood in supplying the auxiliary heat.

Of course, any wood-heating system the college may adopt should be designed such that the annual demand for wood fuel does not exceed the annual sustained yield of the college forest. The Patunoff forest inventory is designed to be accurate to within 20% of the true volume figures. The combined annual yield of the three compartments as given by the survey, is 250 cords per year. Thus, the true value lies between 200 and 300 cords per year. It has been decided to use, in subsequent calculations, the figure of 200 cords per year for the annual harvest, including dead wood. This figure accounts for the inaccessability of some of the wood and for any preserves chosen to be set aside.

Cost of Harvesting the Wood

Because of insurance problems and the probable inexperience among student workers, the job of harvesting the fuel wood is deemed to be best carried out by professionals. One local lumberman has expressed willingness to carry out the harvesting with strict accordance to our management program at a cost of $20 per cord (in 1974). Under the type of agreement discussed with the lumberman, the $20 per cord figure would only include the felling and subsequent transport of the wood to an appropriate place on campus. The wood would be unsplit and in four foot lengths. The wood-heating units which are being considered for the wood-solar system can all consume four foot logs. In order to facilitate drying and handling, however, the larger logs will have to be split. Power wood splitters are readily available from farm equipment dealers. A unit capable of dealing with four foot logs can be purchased for $600. The dealer claims that the unit will last 20 years; thus, its capital cost would be $30 per year (in 1974 dollars) over the next 20 years. Adding in 10% per year for maintenance and fuel costs, the final cost for the splitter is then $90 per year.

The labor cost for the splitting and stacking must also be considered. With three students working at $2 per hour at a rate of one cord per hour, the labor cost would be $6 per hour, or $1200 for the year's 200 cords. Note that this is a maximum figure as not all the wood will need to be split.

One final cost which might normally be attached to the production of wood fuel is the cost of protection and storage for the wood. One plan is to store the wood under the solar collectors, so the storage costs would be absorbed by the collector costs.

The estimated final cost to the college for 200 cords of fuel wood in 1974 dollars is then:

Harvesting and delivery.	$4,000
Splitting costs	90
Splitting-stacking labor costs	.1,200
	$5,290/year

In the proposed wood-solar system, when the temperature of the heat storage resevoir falls below a critical level, the auxiliary system is called upon to make up the heat deficit. The deficit could be only slight, on a partly cloudy day for example; or after an extended period of cloudiness it could equal the entire demand of the campus at that moment.

An auxiliary wood-heating plant, then, must have the following aspects:

a. the flexibility to meet all or any part of the heating demand of the main campus

b. be able to consume cord wood, chipping on this scale being uneconomical

c. be a water-heating system, in order to be compatible with the solar system

d. be commerically available either as complete components or through contract

In addition to the above requirements for the wood-heating plant, the cost of the system including the wood should be competitive with an oil-fired auxiliary system. This, of course, ignores the value of self-sufficiency itself, which will be high if the college is cut off from fossil fuel supplies.

The Wood Heating Plant

The cost of fuel oil can be computed in the following manner:

$$\$0.40/\text{gal}/1.47 \times 10^5 \text{ BTU/gal} = \$2.72/10^6 \text{ BTU}$$

The cost of wood fuel is:

$$\$5290/\text{year}/[200 \text{ cd/year})(20 \times 10^6 \text{ BTU/cd}] = \$1.32/10^6 \text{ BTU}$$

The allowable capital cost for the wood system is equal to the cost of fuel oil less the cost of wood procurement. That is,

$$\$2.72/10^6 \text{ BTU of \#2 oil} - \$1.32/10^6 \text{ BTU of wood} = \$1.40/10^6 \text{ BTU}$$

With a usable lifetime of 20 years for the wood-heating plant, the maximum allowable capital expense for the plant is equal to the number of million BTU of wood burned in 20 years times $\$1.40/10^6$ BTU.

$$(200 \text{ cd/year})(20 \times 10^6 \text{ BTU/cd})(20 \text{ years})(\$1.40/10^6 \text{ BTU}) = \$112{,}000$$

This calculation assumes that the difference in cost between 10^6 BTU of oil and wood will remain $1.40 (in 1974 dollars).

The only wood-fired heating plants which were found this summer and which met all the requirements set forth earlier are marketed by Marco Industries of Harrisonburg, Virginia. This company has taken over the production of wood-heating plants of the Riteway design. Their largest boiler, with 350,000 BTU/hr output, sells for $8880. It would take six such units, with a combined output of 2.1×10^6 BTU/hr to cover the college's estimated peak average heating demand of 1.7×10^6 BTU/hr. Meeting this peak exactly is not critical because the furnaces are coupled to the storage system and the demand can be averaged over several hours. The cost of the furnaces would be $53,300 which places the total cost of this wood system well below the cost for fuel oil procurement alone.

It is believed, however, that the Riteway is not the best cord wood combustion design available today and that units of better design can be found at lower cost. There are two main drawbacks of the Riteway furnace. First, the drafting system employs two electric blowers which consume energy, and when they are non-functional due to a power failure, the operating efficiency of the furnace is greatly reduced. Second, the cost of the Riteway is disproportionately high because it is a "dual-fuel" design, able to switch automatically from wood to fuel oil, and to continue to run on oil until the furnace is refilled with wood. The costly oil-burning provisions are unnecessary in the wood-solar system.

One very promising alternative to the Riteway furnaces is to employ evaporators such as are used in maple sugaring. Such evaporators produce great quantities of low grade heat, which would fit in nicely with the solar part of the system. They are also said to be efficient users of wood fuel and are relatively inexpensive.

In order to use the illustrative graphs to be found in the Solar Energy section for the consideration of wood-fired auxiliary heat, the following figures are offered.

If six Riteways were used, their cost per million BTU would be:

$$\$53,300/\$112,000 = x/\$1.40/10^6 \text{ BTU}$$

$$x = \$0.67/10^6 \text{ BTU}$$

Adding their cost to the cost of the wood fuel ($\$1.32/10^6$ BTU), a cost of about $\$1.99/10^6$ should be used. (Note that the Riteways make up the most expensive furnace system considered.)

The other quantity needed to use the graphs is the percent of the total heating demand met by the auxiliary system. That is:

(oil consumption during the 1973-74 heating season was 91,500 gal)

$$91{,}500 \text{ gal} \times 1.47 \times 10^5 \text{ BTU/gal}/20 \times 10^6 \text{ BTU/cd} = 673 \text{ cd}$$

$$\frac{(200 \text{ cd})(100)}{673 \text{ cd}} = 30\% \text{ of the total heating demand}$$

If the expected fuel savings through the proposed energy conservation measures are realized (30% savings), the percent of the heating demand carried by the auxiliary system is:

$$0.70 \times 673 \text{ cd} = 471 \text{ cd}$$

$$(200 \text{ cd})(100)/471 \text{ cd} = 42\% \text{ of the total heating demand}$$

These two calculations assume equal efficiencies in burning the two fuels. Members of an NSF-URP grant at Williams College have measured the efficiency of an Ashley-type space heater at 50%. There is little doubt then, that a modern wood furnace could match the 65% estimated average efficiency of the college oil burners.

Conclusions

In the calculations presented in this section, it is shown that the cost of harvesting, splitting, and stacking 200 cords of wood for use as a fuel is $1.32/$10^6$ BTU or $5,300 per year. This represents 42% of the main campus heat energy consumption, if that consumption is reduced by 30%. At present oil prices, the same amount of oil would cost $10,300.

But these two figures should not be directly compared for four reasons. 1) There are capital costs for a wood combustion system which must be included in the yearly costs. This is figured to be a maximum of $2,700 per year. But it should be remembered that the present oil heating system is not new and will require significant replacement costs in the next twenty years. 2) In order to preserve convenience when changing from oil to wood combustion, energy storage must be provided so that the wood furnaces are not required to provide heat on demand. The capital costs for the storage system, plumbing, and control units are included in the cost of using solar energy (see Solar Energy section). 3) The costs of fuel oil and wood procurement should be calculated over the twenty year lifetime of the wood furnaces. Thus, Equation 6a (Solar Energy section) should be used to calculate the present value of future oil and wood payments. While interest rates and inflation will affect each to the same extent, the rate of increase in prices above inflation will likely affect oil alone. This is because the cost of procuring wood is predominately labor costs and is not expected to increase at a rate significantly greater than inflation, whereas the cost of oil is subject to shortages and therefore increased prices above inflation. 4) If oil shortages lead to rationing, there is an incalculable economic advantage to be using a combination of wood and solar energy for heating.

In the conclusions of the Solar Energy section, it is estimated that a combination wood-solar heating system would save the college at least 120,000 present value dollars over the expected 20 year lifetime of the system.

VII ORGANIC WASTES

Introduction

Marlboro College produces 700 pounds per day of refuse and 130 pounds per day of sewage solids. The utilization of these wastes in an energy self-sufficient system can fill a particularly troublesome niche, that of an energy source for electricity generation.

Although electricity represents a minor portion of the college's total energy consumption, it is one of the most difficult demands to be met with an alternate energy system. But, in an integrated anaerobic digestion system, methane gas can be produced. This bio-gas can serve as a source of high grade energy necessary for electricity production.

Electrical energy self-sufficiency is also of high priority due to the low efficiency of centralized power plants. Through the use of an on-site total energy system, overall efficiency can be increased from 35% to over 90%. In addition, the use of organic wastes in a system such as this would provide a long term solution to two increasingly costly disposal problems: solid waste and sewage.

Anaerobic digestion is certainly not new (most sewage treatment facilities use anaerobic digestion), but the proposed system is innovative in several important aspects. The digester will convert the organic portion of the refuse and the sewage into methane gas. The only major by-product, carbon dioxide gas, will be scrubbed from the bio-gas and will be used to increase the biomass in an algae pond. The algae pond will serve several important functions in the overall system. First, the algae produced will increase the net energy output of the system by capturing solar radiation. Second, the algae, when added to the digester, will partially offset the inherent nitrogen deficiency of refuse. Third, the pond will further serve the difficult function of ultimate residual (sludge) receptor, a problem which has not been solved in sewage treatment facilities.

Further innovations used in this system will include 1) an insulated digester cylinder to keep heat loss to a minimum, 2) a waste-heat recovery system on the dual-fuel diesel electric generators, the waste heat from which will provide all heating necessary for digestor function, and 3) a special sludge mixer and thickener which eliminates the need for a secondary digestion system while achieving high system efficiency.

ORGANIC ENERGY SOURCES

At Marlboro College the existing organic energy resources are sanitary waste water (does not include storm water or garbage), refuse (trash and garbage), and the forest. The forest will only be briefly considered, as wood energy was treated in the previous section. Thus, this section will emphasize the other organic sources of energy.

The average flow of sanitary waste water at the college is about 9 thousand gallons per day. With a maximum, including infiltration, of 15 thousand gallons per day. Thus, 15 thousand gallons per day will be used as the maximum design parameter. Assuming a full time population of 230, and a biological oxygen demand (BOD) production rate of 0.2 pounds/person/day (20), the total daily BOD is 46 pounds/day. Likewise, the total solids production from this waste water is 0.55 pounds/person/day (20) or 126 pounds/day, and the volatile solids production is 0.32 pounds/person/day (20) or 73 pounds/day.

Refuse is produced at the college at a rate of 3.5 cubic yards/day at a density of 250 pounds/cubic yard (21), which amounts to 875 pounds/day. This production is equivalent to 3.8 pounds/person/day, which is the same value as the average state-wide production rate in Vermont (22). The composition of Vermont refuse is presented in Table 12.

Table 12. Composition of Vermont Refuse (22)

Item	%Wet	%Dry	Pounds Per Day*	%Volatile Solids	Volatile Solids lb/day*
Paper	45	42.7	374	97.0	362
Glass	5	5	44	-	-
Metal	6	6	53	-	-
Organic	26	7.8	68	91.2	62
Wood	5	4.5	39	99.5	39
Other	13	-	114	-	-
Total Organic	76	55	481	-	463
Grand Total	87	66	875	-	463

*Values are calculated for Marlboro College.

Using the figures given above, the estimated total quantity of organic energy resources (forest excluded) is 608 pounds/day of total solids (dry weight) and 536 pounds/day of volatile solids.

Possible Utilization Technologies

A survey of the literature was conducted to compile a set of alternative technologies for using the available organic resources. Three basic utilization categories were identified: biochemical conversion, thermal oxidation, and reuse-recycling.

Biochemical conversion includes those processes that depend primarily upon biological activity, which includes anaerobic digestion and hydrolysis-fermentation. Anaerobic digestion is the bacterial decomposition of organic material in the absence of oxygen, resulting in the production of methane and carbon dioxide. Hydrolysis-fermentation refers to two techniques for breaking down organic materials. In the first process the organic materials (usually mostly cellulose) are hydrolyzed to simple sugars. These sugars are then fermented in the second process to ethyl alcohol (23) or are used to grow single cell protein (24).

Thermal oxidation includes those processes that rely upon high temperatures and chemical reactions to convert organic material to usable energy forms. One such process is pyrolysis, the high temperature oxidation of carbon compounds in an oxygen deficient atmosphere to yield charcoal, methane, organic acids, and other products (25). Techniques for hydrogasification of organic wastes into hydrogen and methane have been patented (26). Wet air oxidation (27) and burning of the wastes were also considered.

Elimination of Technological Alternatives

Over 300 letters were sent to commercial firms, trade associations, and individuals in an attempt to locate sources of packaged systems or the major components of the energy reclamation systems outlined above.

Since no commercial systems were found for the hydrolysis-fermentation of refuse, this alternative was not considered, although its feasibility cannot be ruled out.

Pyrolysis is technologically more complex than any of the other alternatives. This complexity requires a system which is more difficult to maintain and which is not practical unless the end products are significantly superior to those produced by other systems. The products of pyrolysis are methane, charcoal, and a complex mixture of organic acids and alcohols. This set of products may be highly favorable to the chemical industry but presents problems in energy recovery. The products are of three different phases: solid, liquid, and gas. Each must be handled separately, and each requires separate equipment for burning. Also, the liquid fraction would be of little value on a small scale due to the high cost of fractionation prior to use.

Several of the other thermal processes are still being developed or are in the pilot plant stage. None of these processes are considered economically feasible at a plant size of less than one ton/day. The break-even point is believed to be in the size range of 100 to 500 tons/day.

In the past, wood has served as the feedstock for certain chemicals such as wood alcohol (methyl alcohol) (28). Wood has also been gasified and converted to synthetic petroleum for the internal combustion engine (29). Due to the similarity between refuse and wood [refuse being 40 percent cellulose (30)], an attempt was made to locate equipment for these processes. However, after the conclusion of World War II, wood ceased to be a chemical feedstock. Today, not a single wood chemical plant (except charcoal production plants) is in operation in the United States. Wood conversion processes, therefore, were eliminated from consideration even though technological feasibility was not disproved.

A survey of reuse-recycling possibilities was conducted. For any recycling scheme, separation is necessary, but no economical mechanical separation system could be found because of the low refuse output of the college. There are no markets for bi-metal cans in New England, and the closest smelter accepting cans is located in Montreal, Canada.

There are secondary paper dealers in the area, but they require a degree of separation which is economically prohibitive. And, as a result of the Vermont beverage deposit law, the most valuable fraction of solid waste--aluminum--has been virtually eliminated. Thus, the separation problem, the absence of aluminum, and the lack of secondary material markets make reuse-recyling of refuse highly uneconomic.

Anaerobic digestion has been used for over 100 years. Septic tanks and Imhoft tanks use this process, and anaerobic digestion is the most widely used method of municipal sewage sludge treatment in the United States today, although for the past 15 years aerobic digestion has become more common in new treatment facilities. Thousands of small farms around the world use anaerobic digestion to treat domestic and animal wastes while providing methane gas for on-site use (31). Anaerobic digesters are common throughout India where construction and operational technologies are minimal.

Research has also shown garbage and organic refuse to be anaerobically digestible (32). Due to the low level of technology required, the availability of equipment, and long experience, it has been concluded that anaerobic digestion has the greatest probability of proving economically and technologically feasible on the college's scale.

System Design

The emphasis in anaerobic digestion has been upon reduction in volume and stabilization of sludge. Methane gas has been treated as an incidental by-product. A detailed review of the developments in anaerobic digestion theory and operation has been presented elsewhere (33).

Anaerobic digestion is a complex biochemical process in which added organic matter is digested in the absence of oxygen by a mixed culture of bacteria to produce primarily methane and carbon dioxide. In this process, complex organic molecules are first hydrolyzed to simpler molecules, catalyzed by extra-cellular enzymes secreted by facultative and strict anaerobic organisms. The simpler molecules are then converted to volatile fatty acids, alcohols, aldehydes, carbon dioxide, hydrogen, and the cell mass of the acid-forming bacteria. These end products of acidogenesis, with the exception of carbon dioxide, are used as substrates by the methane-forming organisms to yield primarily methane and more methanogenic organisms.

This is an integrated waste management and energy production system which is nearly closed, achieving a high degree of recycling. Solar energy is the prime mover of the system as the sun is the ultimate source of energy in the production of all organic matter. Although much of this organic matter flows to the college from without, an anaerobic digestion scheme will represent a significant improvement over the wasteful practice of land-filling organic materials.

System Description (see Figure 18)

As the raw waste water enters the plant, it is screened to remove large objects, comminutated (ground) to reduce particle size, and sent to a primary sedimentation tank where most of the organic material is removed for later addition to the digester.

It would be economically prohibitive to effect in-plant mechnical separation of inorganic and organic refuse. Thus, all organic refuse must be placed in a separate hopper. The storage time in the hopper should be kept to a minimum to reduce odors and health problems and to maintain a constant flow to the digester.

From storage the refuse will be shredded to achieve a nominal particle size of one to three inches, although it is not clear as to what the optimum size is. It has been reported that a four-fold increase in methane production occurs when 30 mesh particles are used in place of one inch particles (34). But it has also been reported that one inch particles are completely broken down during digestion (27). If particles smaller than one inch prove to be necessary, the cost of size reduction equipment will be greatly increased. A wet size reduction system is preferable, although a dry reduction process could be used if the reduced refuse is mixed with water effluent from the primary sedimentation tank to reach four to eight percent solids.

diamonds indicate
optional processes

ANAEROBIC ENERGY SYSTEM

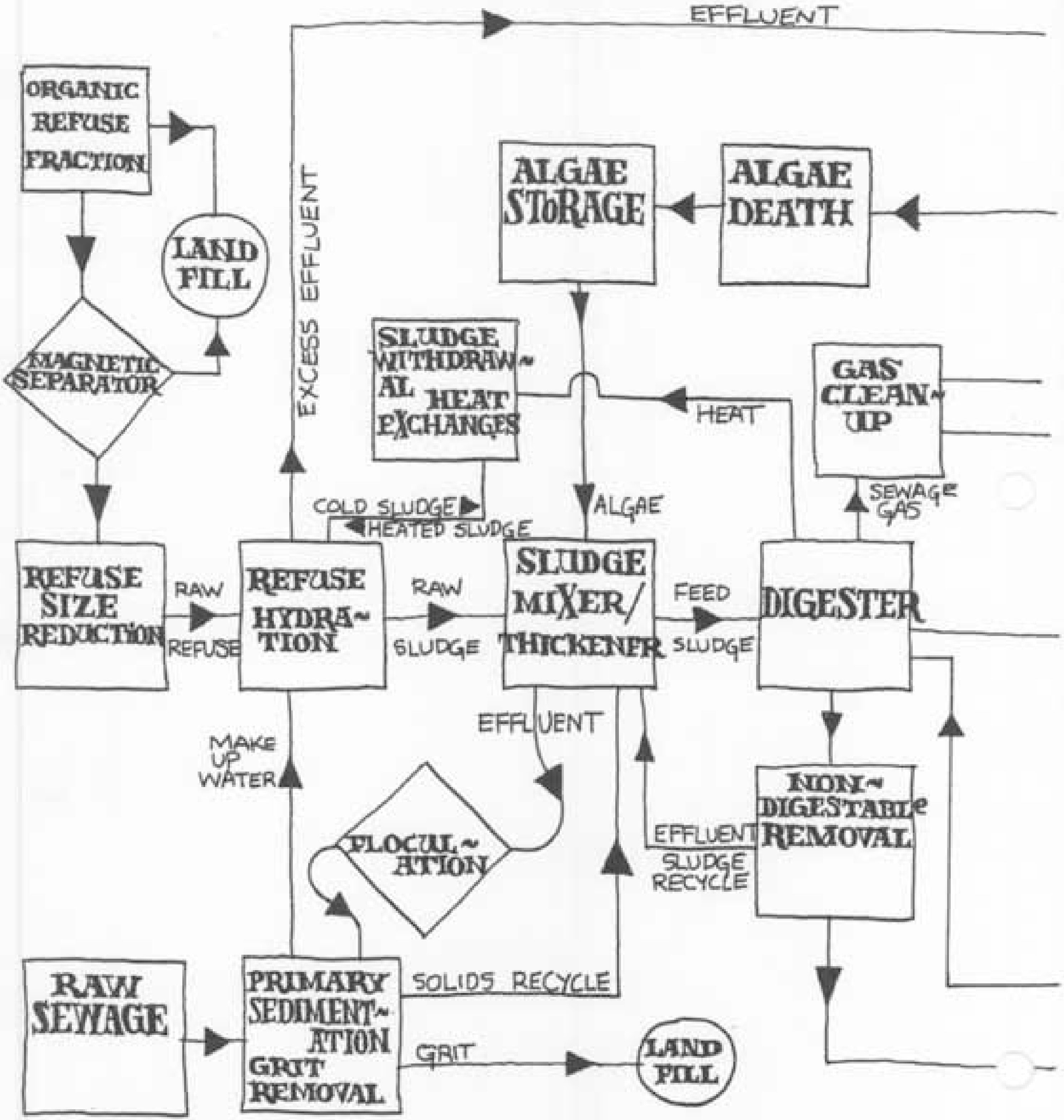
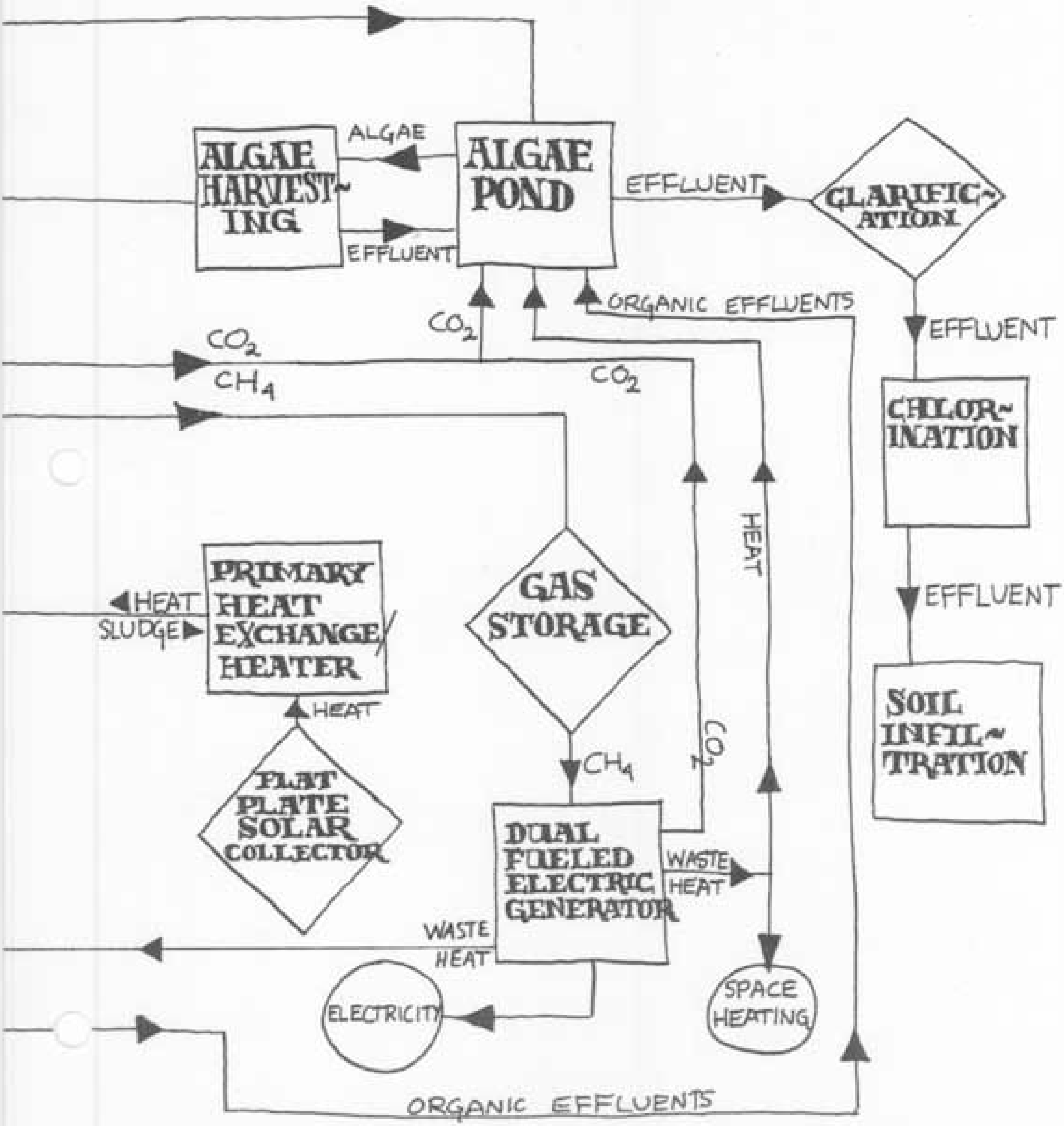


Figure 18.


ALGAE
ALGAE HARVEST-ING
ALGAE POND
EFFLUENT
EFFLUENT
CLARIFIC-ATION
CO2
ORGANIC EFFLUENTS
EFFLUENT
CO2
CH4
CO2
CHLOR-INATION
HEAT
PRIMARY HEAT EXCHANGE HEATER
HEAT
SLUDGE
GAS STORAGE
EFFLUENT
SOIL INFIL-TRATION
HEAT
FLAT PLATE SOLAR COLLECTOR
CH4
CO2
DUAL FUELED ELECTRIC GENERATOR
WASTE HEAT
WASTE HEAT
ELECTRICITY
SPACE HEATING
ORGANIC EFFLUENTS

The organic refuse slurry from the shredder and the raw sewage sludge from the sedimentation tank are then both fed to a mixer-thickener where an equal volume of activated sludge from the digester is pumped. The three sludges are then thoroughly mixed, flocculated if necessary, and allowed to thicken to eight percent solids. This thickened sludge mixture is then pumped to the digester. Water effluent from the mixer-thickener is returned to the primary sedimentation tank to increase solids and BOD removal.

Digester Operation

The digester is a square, right circular cylinder to maintain a high volume to surface area in order to minimize heat loss. To further minimize this loss and to provide support so that the walls do not have to withstand the full outward thrust of the contents, most of the digester is placed underground.

Twice a day, 1/30 of the contents of the digester will be removed and processed to remove grit and other non-digestible material which will be land-filled. One half of the remaining digestible material will be pumped to the mixer-thickener for eventual return to the digester. The other half will be sent to the algae pond for aerobic decomposition and eventual recycling to the digester in the form of algae bio-mass. These withdrawals are frequent and of small volume so as not to upset the ecological balance of the digester.

The digester should also be fed often, at least once or twice a day. Thus, the mixer-thickener will not have to be very large to accomodate these small volume transfers. The retention time in the mixer-thickener should be as short as possible since most gas production occurs in fresh sludge. It may prove advantageous to equip the mixer-thickener with gas recovery equipment if the gas yield is large.

The digester will be heated by an external heat exchanger using exhaust heat from a dual-fuel diesel electric generator (see section on Electrical Generation). Incoming and outgoing sludge represent the major energy expenditures in heating the digester. It is important, then, to keep hydraulic flows to a minimum. In order to recover the heat contained in outgoing sludge, a heat exchanger will be installed to transfer heat to the organic refuse slurry going to the mixer-thickener.

The digester should also be equipped with a device to remove any scum or floating material that may accumulate on the surface of the sludge.

Gas Removal

The gas produced in the digester will be removed and scrubbed in an iron sponge to remove hydrogen sulfide which should constitute well less than one percent of the bio-gas because of the high proportion of low-sulfur cellulosic wastes being digested. The remaining bio-gas will be separated into methane and carbon dioxide fractions. The carbon dioxide will be diffused through the algae pond in order to increase the growth rate of the algae and to prevent the pond from freezing in the winter. The methane will go to a short-term, small volume storage vessel to allow for irregularities in gas production and consumption. The gas will be used to run a dual-fuel, diesel electric generator. Using a heat exchanger, engine exhaust can provide all of the necessary heat for the digester and possibly some for building heat (see the Electrical Generation section). The carbon dioxide produced in the generator by methane combustion can also be diffused through the algae pond.

Algae Pond

The algae pond is similar in design to several other bio-solar energy systems (35). However, this algae pond will serve additional functions and, therefore, will have a more complex mixture of micro-organisms in order to accomplish these multiple functions. Other proposed ponds have been intended to treat waste water by using sewage as a carbon and nutrient source to provide bio-mass for ingestion or power production.

The function of this algae pond is five-fold:

1) To provide for final disposal of residual solids.

2) To trap nutrients from outgoing sludge and thus upgrade the quality of the final effluent.

3) To maintain a suitable carbon-nitrogen ratio in the digester through atmospheric nitrogen fixation.

4) To provide an increased bio-mass for the digester which will increase gas production.

5) To provide for ultimate hydraulic disposal from the primary sedimentation tank and the digester.

Without an algae pond, expensive sludge de-watering and drying would be necessary, and sludge removal would become a significant problem. Refuse is normally nitrogen deficient so that inorganic nitrate or ammonia compounds are usually added. By fixing nitrogen, the algae pond will greatly reduce if not eliminate the need for the addition of inorganic nitrogen. The algae pond can be increased in size in order to generate whatever amount of methane (bio-mass) that is ultimately desired. It appears feasible that a combination of algae, organic refuse, and sewage will produce enough methane to generate 100 percent of the college's main campus electrical energy needs.

Presently, at Marlboro College, there is a problem with the diffusion of waste water into the ground. A long infiltration trench is planned (by others) for the future. Construction of an algae pond instead could provide a large enough area for atmospheric evaporation and soil infiltration that the need for a trench system could be eliminated.

Water flowing out of the algae pond will undergo clarification (if necessary) and chlorination (if necessary) prior to soil infiltration.

The pond will be shallow, possibly eight inches deep, in order to allow photosynthesis throughout its entire volume. It will be mixed to facilitate contact between the different groups of decomposing (bacteria) and synthesizing (algae) organisms. A mixed culture will be used in order to foster, concurrently, nitrogen fixation, carbon dioxide fixation, and aerobic sludge decomposition. To increase algae production, it would be advantageous to heat the pond and enclose it to retain carbon dioxide.

The hydraulic detention period will be in the range of two to six days to maximize growth while maintaining harvesting frequency at a reasonable level. Two methods of harvesting the algae, chemical coagulation and centrifugation, have been proposed (35). Centrifugation is preferred due to the possible adverse effects of chemical coagulants on the digester. To reduce costs, autoflocculation should be used as much as possible.

If the digester is operated at mesothermic temperatures (95 degrees Fahrenheit), the algae must be killed prior to introduction into the digester, otherwise they will survive and reproduce, avoiding decomposition. Although a thorough examination of possible killing techniques has not been possible, air drying seems to hold promise because it is inexpensive and facilitates storage during summer months. Due to the variation of solar intensity and angle of incidence over the year, algae production will vary. But a constant feed to the digester should be maintained so a portion of the summer production can be stored for later use to bring winter digester input up to the average production.

Technical Specifications and Commercial Products

Due to the small waste water flow at Marlboro College, i.e., less than 15,000 gallons/day, commercial equipment for the system has been very difficult to locate, but, fortunately, appropriate components have been found for nearly every requirement.

Primary Sedimentation

Normally, in municipal sewage treatment plants, primary sedimentation is performed separately from screening and comminutation, but an unusual piece of equipment has been found which can accomplish these three operations simultaneously.

The Bauer Hydrasieve (36) will cost one-tenth the amount of separate comminutation and sedimentation equipment. Accomplishing its action through special screens, the hydrasieve has no moving parts and requires no supervision. The size of the screening may be varied to obtain the desired degree of solids removal. With a 0.020 inch screen, a flow rate of eight to ten gallons/minute can be achieved (37). This is large enough to allow both for severe peak flows and for effluent recycling. This size screen will produce results comparable to normal primary sedimentation, i.e., 40 percent solids removal, but it may prove advantageous to install two of these units in series, the second with finer mesh screening, in order to achieve a very high degree of solids removal. The cost of the Hydrasieve is $900 (37).

Usually, grit is removed from the waste water flow after screening and comminutating. But the Hydrasieve can be equipped with a Bauer Centri-Cleaner Liquid Cyclone (38) to accomplish this grit removal. This unit is superior to normal grit-removal devices in that it functions as part of the Hydrasieve and it does not use aeration processes which are counterproductive in an anaerobic digestion system. The cost of this unit is $130 (37).

Organic Solids Size Reduction

The size reduction system is designed to process the college's present organic refuse production of 700 pounds/day plus an additional 500 pounds/day that may be necessary to supply enough energy to provide 100 percent of the main campus electrical demand. Since the size reduction system will only operate five days/week, a capacity of 1700 pounds/day will be required. Based on a five hour/day actual operating period, the capacity of the shredding unit will be 350 pounds/hour.

Companies which manufacture size reduction equipment include the following:

Jeffrey Manufacturing Company
Walker Process Equipment
Denver Equipment Division
Gruendler Crusher and Pulverizer Company
Williams Patent Crusher and Pulverizer Company
Mitts and Merrill Company
Pennsylvania Crusher Corporation

Mixer-Thickener

The mixer-thickener will be similar to a standard gravity sludge thickener. Additionally, the unit will be equipped with a mixing cycle and special mixing blades if necessary. Flocculation equipment may be added to increase thickening and to achieve a cleaner effluent. The unit has a capacity of 10,000 gallons, is 8.11 feet in diameter, and has a surface area of 314 square feet.

The mixer-thickener is important to the successful and economical operation of the digester, for the solids content of the sludge is a direct determinate of the size of the digester. For example, for 1,100 pounds of solids, a 4 percent slurry amounts to 3,300 gallons/day added to the digester, while a 10 percent slurry amounts to only 1,320 gallons/day.

Input to the digester should also be at a high solids concentration in order to reduce the amount of sludge heating required. However, at high solids content, digester mixing requires more energy. The optimum degree of sludge thickening is not known.

The cost of the mixer-thickener is about $7,300 (39).

Digester

Assuming a 6 percent solids concentration, a 15 day hydraulic detention period, and a recycle factor of 1.3 (40), the volume of the digester should be 5,700 cubic feet or 44,000 gallons. In order to use commonly available equipment and the thermal advantages of a square, right circular cylinder, a 20 feet diameter, 20 feet deep digester was selected. This results in a volume of 6,280 cubic feet or 49,000 gallons. In terms of volatile solids loading with this digester configuration, this is 0.166 pounds/cubic feet/day, which is well within established limits (41).

The digester will be buried and back-filled so that two feet of the tank extends above the ground. The internal temperature will be maintained within one degree of 95 degrees Fahrenheit as it has been concluded that at present the greater stability of mesophilic digestion outweighs the greater solids destruction and shorter detention time of thermophilic digestion at 140 degrees Fahrenheit. If research demonstrates the stability of the thermophilic operating range and concurrent heat loss problems can be solved, the higher temperature range should be used.

Heat loss has been calculated using standard thermodynamic practices. With 3 inches of styrofoam insulation and a plywood cover, during the coldest month, February, with an ambient mean temperature of 18 degrees Fahrenheit, heat loss is as follows:

Table 13. Digester Heat Loss

	BTU/HOUR
Lid	817
Tank Above Ground	244
Tank Below Ground	5410
Total	6470

Assuming a 3,300 gallon/day withdrawal from the digester, with 90 percent of that heat transferred to the organic refuse slurry, an additional 740,000 BTU/day will be necessary to heat the sludge. With a twice daily transfer, the sludge withdrawal heat exchanger must have a capacity of 170,000 BTU/hour.

The micro-organisms in the digester will produce a significant amount of heat. Assuming a production of 10,000 cubic feet/day of bio-gas at a 35% carbon dioxide concentration, 29,000 BTU/day will be produced by the organisms.

Table 14. Digester Heat Balance

	BTU/DAY	BTU/HOUR
Sludge Heating	740,000	31,000
Heat Loss	115,000	4,800
Biological Heat	-28,800	-1,200
Total	826,000	34,600

An equation has been developed to calculate the cost of a digester tank (42).

$$C = V(1.65 + 17/V^{0.87}) \qquad (7)$$

where, C is the cost in thousands of dollars

and, V is the digester volume in thousands of cubic feet

For a digester of the size appropriate to the college,

$$C = 6.3(1.65 + 17/613^{0.87}) = 18 \ (10^3 \text{ dollars})$$

Since this is a January 1973 cost, an inflation factor of 1.3 is used to update this cost to $23,000. An outside estimate for a bare tank is $13,400 (39). After including necessary extra costs, the discrepancy between the two figures should be small.

Digester Mixing Systems

1) Pacific Flush Tank--Pearth System

2) Ralph B. Carter Company--Aero-Hydraulic Method

3) Chicago Pump Division--Shearfuser Diffuser

4) Dorr-Oliver--Draft Tube Digester

Of the four digester mixing systems listed above, the Pearth system is the only one for which cost data could be obtained. It is possible that one of the other systems is as effective and less expensive than the Pearth system. It appears that the Shearfuser diffuser may cost a fraction of the Pearth system. Further investigation on the effectiveness of each system is needed in addition to more cost data.

Digester Process Control

To insure efficient and dependable operation of the digester, monitoring devices and control systems should be included. Monitoring of at least the production and composition of volatile acids and pH should be included. Chemical feed systems to correct for pH variations and nutrient deficiences should be provided.

Non-Digestible Material Removal

It would be highly advantageous to remove non-digestible material (usually inorganic grit) which occupies volume resulting in reduced digesting space. This material also increases mixing power requirements and increases wear on pumps and other equipment. Due to the high density of most of this undesirable matter, several possible cleaning devices exist. The equipment that appears to be best for this task are the Dorr-Oliver MercoBowl (centrifugal dewatering unit) and the DorrClone (grit washer). Dorr-Oliver has designed these two units for non-digestible material removal prior to digester charging, but adaptation to positioning after charging is believed possible. Other equipment which is available for this task are the following:

Jeffrey Manufacturing Company--JI Grit Washer
Walker Process Equipment--Grit Separation Unit
Denver Equipment Division--D-R Denver Flotation Machine and Denver Hydro-Classifier

Gas Storage

Normally, gas storage is provided by excess capacity in the digester with the gas contained under the floating cover. But in a system where the gas is to be used productively, as opposed to municipal treatment facilities where excess gas is burned in the atmosphere, additional gas storage is desirable. Carbon dioxide should be removed from the bio-gas prior to storage as this will reduce the volume by 20 to 40 percent.

Firestone's Fabritank appears to offer the lowest cost method of auxiliary gas storage. The tanks are available in a wide range of sizes. As an example, a 10,000 gallon tank with a storage capacity of 1.3×10^6 BTU would cost $4,300.

Support Facility

A building to house controls and piping will have to be constructed. This will be a minimal structure but well insulated. Heat will be provided by the exhaust from the diesel engines. It is estimated that the cost of this building, including site preparation, would be about $20,000. Since it is a minimal structure, this building could easily be built with local or student labor.

Capital Costs

The projected capital costs of this system are included in Table 15.

Table 15. Capital Costs of the Anaerobic Digestion System

ITEM	COST	REFERENCE
Chemical Feed System	$1,000	43
Mixer-Thickener	7,300	39
Hyrasieve and Liquid Cyclone	1,000	44
Sludge Withdrawal Heat Exchanger	2,000	45
Comminutator	5,700	46
MercoBowl Centrifuge	2,000	assumed (48)
Primary Heat Exchanger	18,000	45
Sludge Pumps	15,000	47
Digester Tank	23,000	42
Digester Floating Cover	35,000	47
Digester Mixing System	20,000	47
Gas Clean Up	1,000	assumed
DorrClone Grit Washer	2,000	assumed (48)
Gas Piping	20,000	assumed (47)
Purchased Equipment Cost	$162,000	
Installation Cost (20%)	32,400	
Installed Equipment Cost	$194,400	
Support Facility	$20,000	
Total Capital Investment(w/o algae pond)	$214,400	
Optional Equipment		
Gas Storage Fabritank	$4,300	49
Algae Pond: 1 acre	20,000	assumed
Mixer-Thickener Flocculation: Floctrol	8,000	47

The cost of the algae pond has been left out for three reasons. First, an adequate cost estimate could not be made because such ponds are not commercially available. In addition, the cost would greatly depend upon whether cover provision and heating during the winter were provided. Second, although it is beyond the scope of a report on energy self-sufficiency, an algae pond may not be needed because local restaurants, residents of the Town of Marlboro, and non-resident college employees have all expressed a willingness to provide organic wastes to the college. Indeed, the Town of Marlboro pays for the right of its citizens to transport their own refuse to the Brattleboro land fill twenty miles away. Third, in view of the possibilities for receiving extra-campus organic wastes, the necessary size of the algae pond is open to question. Should it be felt necessary to build a pond to facilitate sludge and hydraulic disposal, it is estimated that a minimal pond 1 acre in size could be built for about $20,000 if a relatively level spot can be found.

Economics

A full comparison of the costs and benefits of an anaerobic waste treatment facility will be included in the section on Electrical Generation. However, values directly applicable to anaerobic digestion will be made under this subheading. For a summary of capital costs, see Table 15.

Expected Energy Production

Gas production may be calculated using the following equation:

$$E = WDRCe \qquad (8)$$

where,
- E is the energy produced in BTU/day
- W is the mass of volatile solids added to the digester per day
- D is the percentage of solids destroyed
- R is the quantity of gas produced per pound of solids destroyed (in ft^3/pound)
- C is the percentage of methane in the bio-gas
- e is the energy content of the methane in BTU/ft^3

The value of <u>e</u> is a constant equal to 1,200 BTU/ft^3. <u>W</u> will be held constant at 1,000 pounds/day or approximately twice the amount of the college's organic refuse. Equation 8 then reduces to,

$$E = 1.2 \times 10^6 \ DRC \qquad (9)$$

Due to the large number of ill-defined system parameters, such calculations are fairly imprecise. Therefore, a minimum and maximum probable range of energy production will be given.

Table 16. Gas Production Values

	D (Percentage)	R (ft^3/lb)	C (Percentage)	E (BTU/Day)
Minimum Value	0.65	9	0.65	4.6×10^6
Maximum Value	0.95	20	0.75	17.1×10^6

It would be safe to use a value of 10.9×10^6 BTU/day (average of minimum and maximum values) for the energy production because the digester system is designed to accommodate a larger solids input. Thus, if the actual value is somewhat lower than the average, additional organic material from a variety of sources may be introduced. With the space and economic problems of organic waste disposal that exist today, obtaining a small amount of additional organic wastes should be confronted with no economic barrier.

Present Refuse Disposal

Presently, Marlboro College hauls its solid waste to the Brattleboro land fill. The cost of using this service has been rising sharply. The privilege cost is now $2,700/year. In addition, the college must devote 10.5 person hours/week for collection and hauling, and the truck mileage is 105/week. At $3/hour for labor and $0.15/mile truck expense, this amounts to $47/week or $2,460/year. Thus, the total expense, including land fill use, is $5,160/year.

With an anaerobic digestion system, most of the hauling would be eliminated because most of the refuse is organic, and non-organic refuse has a higher density thus requiring less truck volume for a similar mass. It is estimated that the hauling distance would be reduced to 15 miles/week and the labor cost would be cut in half. Since glass and metal are not putrescible, hauling could be done when a full load accumulates or about every three weeks. This is estimated to have a mass of about one ton. The yearly labor and mileage cost would be reduced to about $210. With this reduced hauling, there would be a land-fill credit of $2,360/year.

The net benefit of converting to an anaerobic digestion system is then $4,610/year. It should be remembered that to calculate the amount of this saving over the 25 year expected life of the digester, the present value should be calculated (Equation 6a in the Solar Energy section). It will be assumed for the sake of simplicity that this cost is just,

25 years x $4,610/year = $115,300

Planned Aerated Lagoon System

At present an aerated lagoon system is planned (by others) to alleviate the wastewater infiltration problem mentioned earlier. The lagoons will occupy one acre. A soil infiltration ditch approximately 1300 ft x 120 ft will be used to discharge the chlorinated effluent. The total area to be occupied by this system is about 4.6 acres. The capital cost of the system will be about $81,000. Operating costs will be low. Labor will be 2.5 person hours/day at $3/hour or $2,740/year. Power requirements will be 5 HP used intermittently. Assuming 12 hour/day operation, at present electrical rates the cost will be $650/year.

Thus, the total yearly cost of the aerated lagoon system will be $3,390. Again, this cost should be figured for comparison to the 25 year expected life of the digester by use of the present value equation (Equation 6a). For simplicity, the 25-year present value is assumed to be equal to,

25 years x $3,390/year = $84,800

Thus, the 25 year cost of constructing and operating the aerobic lagoon treatment system is $165,800.

Operation and Maintenance Costs of the Anaerobic Digestion System

An equation has been developed to express operation and maintenance costs as a function of fluid flow (50).

$$\log Y = 0.7298 \times \log X + 4.5039 \qquad (10)$$

where, Y is the total annual operation and maintenance cost
X is the flow in millions of gallons per day

This expression has been found to have a correlation coefficient of 0.90.

Although the maximum flow at Marlboro College is 0.015×10^6 gallons/day, a value of 0.030×10^6 gallons/day will be used in the calculation to account for the greater solids loading due to refuse inclusion. Thus,

$$\log Y = 0.7298 \times \log 0.030 + 4.5039$$

$$Y = \$2,350 \qquad \text{(in September 1970)}$$

This cost figure must be updated, and it is convenient to update to mid-1974. Operation and maintenance costs are assumed to be composed of 40% labor, 20% electrical power, and 40% materials. The labor fraction has been escalated according to the average of the ENR skilled and common labor indices (1.348). Thus, in mid-1974 the labor fraction is $1,290.

The power requirement of the system is increased by the energy-intensive size reduction process. However, it is also reduced by the relatively great amount of energy required to heat the digester which already has been taken into account in the energy production calculations (the digester to be heated with diesel engine waste heat). The cost of electrical power has increased by 30% since September 1970. Thus, the electrical cost is $610.

Materials costs have been escalated according to the ENR materials cost index inflation factor of 1.489 to give a figure of $1,400.

The total yearly cost (in 1974) of operation and maintenance is $3,300. Again, instead of using the present value equation, for simplicity it will be assumed that the total operation and maintenance costs over the 25 year expected life of the digester are,

25 years x $3,300/year = $82,500

Costs Summary

The costs to the college for this anaerobic digestion system are for capital investment and operation and maintenance costs. The savings are for reduced refuse disposal costs and for eliminating the need for aerated lagoons. These values are summarized in Table 17. But it should be remembered that these costs do not take into account the value of the methane produced. A total cost analysis will be included in the next section of Electrical Generation.

Table 17. Costs Summary of Anaerobic Digestion System

Capital Costs	$214,400
Operation and Maintenance	82,500
Present Refuse Disposal	-115,300
Aerated Lagoon System	-165,800
Total Cost	$15,800

This table does not take into account the cost of the mixer-thickener flocculation device ($8,000), the gas storage tank ($4,300), the algae pond capital cost ($20,000), and the operation cost of the algae pond (assumed to be the same as those of the aerated lagoon system, or $84,800). Adding these costs to the Total Cost figure in Table 17, a value of 132,900 present value dollars is obtained. This is a yearly cost of $5,320.

Possible Cost Reductions

It is believed that it is possible to achieve a substantial reduction in the capital costs of the anaerobic digestion system. It is expected that this may amount to about 15 or 20 percent of the capital costs or $32,000 to $43,000. The items most likely to permit economization are: sludge pumps, digester mixing system, gas piping, and digester floating cover.

If surplus equipment can be located, a further reduction in cost can be expected. Since many older, smaller anaerobic systems have been decomissioned, it seems probable that some suitable equipment can be found. It is estimated that this might represent a savings of 10 percent of the capital costs or $21,000.

Conclusions

Cost Conclusions

For the purposes of evaluating the total cost of the anaerobic digestion system for comparison with the economic benefits of methane gas production, the following assumptions are made:

1) The 1 acre algae pond will be needed.

2) The mixer-thickener flocculation device will not be needed.

3) The gas storage tank will be needed.

4) Economizations will result in a capital expenditure reduction of $25,000.

5) Surplus equipment will allow a capital expenditure reduction of $10,000.

Thus, the final figure that will be used for cost comparison purposes is 90,000 present value dollars, or $3,600/year over the 25 year expected system life.

Further Research

The following is a list of areas and problems which need further investigation. Active research is now being carried out in several of these areas and results can be expected to appear in the literature within a few years. Other areas will require either research carried out at Marlboro College or improved calculations using existing information .

1) The degree of sludge thickening which is optimal, and the effect of thickening on sludge pumping, heating, mixing, and digester size.

2) The optimum carbon-nitrogen ratio for digester methane production.

3) Degree of mixer-thickener insulation.

4) Optimum particle size in digester feed. This affects size reduction requirements, efficiency of digestion, and solids retention time.

5) Quantity of gas to be stored to even out production and demand.

6) The practicality of mixer-thickener gas recovery equipment.

7) Size of the algae pond; possibility of covering and heating algae pond; proper algae species for optimum growth; best method for algae death.

8) The possibility of wood digestion, possibly using sawdust from sawmills.

9) Advantages of mixer-thickener flocculation device.

10) Best equipment for digester mixing and for separation of non-digestible solids from sludge withdrawn from the digester.

11) Method for carbon dioxide removal from bio-gas and for diffusion through algae pond.

12) Advantages achieved through the inclusion of small amounts of low-grade coal in the digester.

VIII ELECTRICAL GENERATION

Introduction

The generation of electrical energy is a particularly difficult problem to be overcome in designing a self-sufficient system. This is due primarily to the fact that electricity is a high grade energy. Still, there are several sources of that energy available on the Marlboro College campus. For instance, there is wind, which in conjunction with a wind conversion device, can generate electricity. There is hydroelectric power (see the next section) which can be used. Solar energy (see Solar Energy section) can be used for the direct generation of electricity. But each of these potential sources of energy suffers from severe economic drawbacks. Because direct generation of electricity with solar energy and hydroelectric power are treated in other sections, only wind power generation economics will be dealt with here.

There are two other potential sources of electricity: combustion powered generation using wood or methane as a fuel. Since all of the allowable cut of wood will be best used for the generation of heat (see section on the Marlboro College Forest as an Energy Resource), only methane combustion will be considered in this section.

Wind Power

The energy contained in the wind is free and non-depletable. But it has not proved easy to harness. With the rapidly increasing electrical rates of the last year and with a dwindling of fossil fuel supplies used for electrical generation, perhaps some companies will begin large-scale production of wind energy conversion devices to satisfy an eager market. As it stands now, these devices are not economical, and the problem of energy storage for windless periods has not been solved because of lack of large company capital involvement.

Electrical Demand

The main campus uses electricity at a rate of 3.25×10^5 kilowatt-hours/year (KWH/year). This is an average power demand of 37 KW, with Peak demands in the vicinity of 80 to 100 KW (see Table 18).

Whatever system is adopted, electrical generation for the college must be flexible enough to meet the peak demand without difficulty and whenever it might occur, preferably at an investment that is competitive with the current costs of electricity.

Table 18. Main Campus Electrical Demand

MONTH	ENERGY (in 10^3 KWH)	POWER (KW)
January	34	46
February	25.5	38
March	28.5	38
April	39.5	55
May	28	38
June	20.5	28
July	30	40
August	11	15
September	18.5	26
October	41	55
November	27.5	38
December	13	17
Average:	27	37

Wind Conversion Economics

For the reasons mentioned previously, wind-powered generating systems are among the most expensive means of obtaining electricity available today. The units which are available are quite small. For example, the largest available generator, made by Elektro-gmbH of Winterthur, Switzerland, is a 6 KW DC unit, 5 KW in its AC version.

A complete wind generating system from Solar Wind Company that is rated at 700 KWH/month in an area of 10 MPH average wind speed is priced at $17,500 (51). This system includes wind generators, towers, voltage regulators, storage batteries, and miscellaneous equipment. A system to supply the college's needs would require 39 such units at a capital cost of $682,500. Over the 20 year expected operating life a total of 6.5×10^6 KWH would be generated at a cost of $0.105/KWH. Maintenance costs are expected to amount to an insignificant contribution to the total cost of the system.

In a twenty year lifespan, the energy generated by this system will cost more than 10 cents/KWH which is 2.8 times the 3.7 cents/KWH paid by the college in 1973. Although commercial electricity may soon reach this cost, it is felt that such a huge capital investment could not be made on such a weak basis.

The prospects for wind-generated power at the college are subject to two other drawbacks. The more significant one is the severe lack of current wind data, or indeed any wind survey at all. It appears likely that in the near future, the cost of wind-generated power will decline significantly. For this eventuality, the college should have a thorough wind survey, because the amount of available energy in the wind increases as the cube of its velocity. Thus, a wind velocity of a few miles per hour greater than the regional average could make the system economical. Golding states that a thorough anemometer survey should be conducted for at least one year on the site of any proposed wind power plant in order to be reasonably sure of the amount of wind to expect (52). At the moment there is no source of wind data within a twenty mile radius of the college (53). By the time that an on-campus wind-generated power system might actually be installed, the survey information having been available for some time would be the basis for a recommendation.

The second added drawback is that Marlboro College lacks appropriate areas of land which could serve as sites for the wind generators. The college is situated on the south slope of an 1,800 foot ridge in a very mountainous area. There is no land that is not at least partially sheltered by nearby peaks, and there is no land that is exposed to the northwesterly winter winds. But it is possible that the college could buy some contiguous acreage which has adequate northwest exposure. It would require purchase of a few acres of west-facing hillside which drops 300 feet in a quarter of a mile.

Wind Energy Conclusions

Although they are not yet economical for areas with average wind velocities, wind-powered electrical generators should not be ruled out for Marlboro College. The current world-wide shortage of fossil fuels is driving up the price of electricity. When large-scale production of larger units drives down the cost of wind conversion devices, the college should reconsider their use.

In the meantime, a thorough wind survey should be made to determine the wind velocity patterns at the college. This is especially critical in view of the fact that the wind energy varies with the cube of the velocity. Thus, a higher than average wind velocity will bring economic parity with conventional electrical energy a closer reality.

Methane Combustion Electrical Generation

Fuel Cells

Fuel cells certainly represent a desirable method for the combination of oxygen and methane to form carbon dioxide and water. They are noiseless, efficient, and do not produce heated exhaust.

But at present they are far too short lived and expensive for serious consideration in this system. Pratt and Whitney has quoted a figure of slightly greater than $100,000 for a fuel-cell system of the size the college would need. But, because of the advantages of fuel cells, should the price decline and longevity increase, the college should reconsider their use. If, as is recommended later, the college adopts a system using diesel engines to combust methane, every several years when the engines wear out, a conversion to fuel cells could be effected with no economic penalty.

Methane-Fueled Diesel Electrical Generation

In the Organic Wastes section, it was determined that 10.9×10^6 BTU/day of methane gas can be produced in an anaerobic digestion system. Since this is a relatively small amount of methane, the efficiency of the engine using it is of great importance. There are several types of engines that are available. Their efficiencies are listed in Table 19.

Table 19. Efficiencies of Various Engines (54)

Engine Type	Thermal Efficiency (%)
Low-compression spark ignition	27-29
High-compression spark ignition	33-38
Open-cycle gas turbine	16
Open-cycle gas turbine with recuperator of 75% thermal ratio	22
Diesel	35-40
Dual-fuel diesel	35-40

Diesel engines give the highest return of usable power per unit of fuel, and the dual-fuel diesel will run on 90 to 95 percent methane and 5 to 10 percent diesel fuel. This engine type has the advantages of high efficiency, long life, relatively low cost, and easily available parts and servicing.

If the fuel supply is 10.9×10^6 BTU/day, and if this is being consumed in a dual-fuel diesel engine with a 7.5% charge of diesel fuel running at 37.5 percent efficiency, the available power is,

$$(10.9 \times 10^6 + 0.82 \times 10^6) \times 0.375 = 4.4 \times 10^6 \text{ BTU/day}$$

converting to KW units,

$$\frac{4.4 \times 10^6 \text{ BTU/day}}{3.413 \times 10^3 \text{ BTU/KWH}} = 1{,}290 \text{ KWH/day}$$

This can be expressed as continuously available power,

$$\frac{1,290 \text{ KWH/day}}{24 \text{ H/day}} = 54 \text{ KW}$$

Since the average main campus electrical demand is 37 KW, it certainly seems likely that the installation of three 40 KW generating sets, for example, would provide the necessary capacity to supply all of the main campus electrical power.

This type of system would also produce 3.7×10^6 BTU/day of recoverable waste heat (55), approximately half of which would be used to heat the sludge in the digester (in the winter). The remaining half could go towards heating the digester and generator buildings or algae pond.

Economics

Dual-Fuel Diesel Plant Costs

Table 20 contains a listing of probable plant costs for the dual-fuel system. The life of the system is 10 years, but for calculating the costs for later addition to the anaerobic digestion costs (system life 25 years) a 25 year calculation must be made.

Table 20. Dual-Fuel Diesel Plant Costs

	10 Year Cost	25 Year Cost
Three 40 KW diesel generators at $150/KW	$18,000	$45,000
Maintenance (10% of engine cost/year	$18,000	$45,000
Diesel fuel	$26,600	$74,900
Generator building, wiring, and switching	$5,000	$5,000
Total Expense:	$67,600	$169,900

Maintenance costs include the cost of rebuilding the diesel generators every 30,000 hours. This cost is subject to the present value equation (Equation 6a in Solar Energy section). For the sake of simplicity, it will be assumed that the rate of cost increase above inflation is zero and that interest and inflation are roughly equal.

The cost of diesel fuel also has to be calculated in present value dollars. It has been assumed that interest and inflation rates are roughly equal but that the cost of diesel fuel will increase at a rate of 4 percent beyond inflation (a doubling in price every 17 years).

Total Cost of Anaerobic Digestion--
Diesel Electric System

The yearly cost of the anaerobic digestion system, as calculated in the Organic Wastes section, is $3,600. The yearly cost of the diesel generating system is $6,800 (25 year figure). Thus, the total cost is 10,400 present value dollars per year for the complete system, or a 25 year total cost of $260,000. This cost should be compared with the electricity costs in Table 21.

Value of the Methane

The total amount of energy generated in 25 years is,

$$54 \text{ KW} \times 8{,}760 \text{ H/year} \times 25 \text{ years} = 1.18 \times 10^7 \text{ KWH}$$

It should be remembered that this energy generation is subject to a fairly large uncertainty. Indeed, the continuous power output could vary from 23 to 85 KW. But it should be reiterated that the actual power figure can be adjusted upwards, if necessary to attain self-sufficiency, by obtaining additional amounts of organic waste from an expansion of the algae pond or from extra-campus sources. This can be done with little added expense to the college. The value of this electricity is included in Table 21.

Besides the costs for continuous power outputs of 23, 54, and 85 KW, the values for 37 and 47 KW are also included in Table 21. The figure of 37 KW represents current main-campus consumption. It is believed that the new theatre building (presently under construction) and either a) the aerobic lagoon system or b) the anaerobic digestion and algae pond system will add approximately 10 KW to the average main campus power draw. Indeed, this must be considered a minimum addition because the theatre building has a maximum rated output of 120 KW and its air-changing system has an output of 22 KW. Only through extremely careful conservation measures will this increase be held to a continuous power draw of 10 KW.

In order to calculate the value of this energy in terms of commercial electricity, it is necessary to use the present value equation. The cost of commercial electricity to the college in 1973 was $0.037/KWH. Again, it is assumed that interest rates and inflation are roughly equal and that commercial electricity prices will increase at a rate of 4 percent beyond inflation.

Table 21. Yearly Electricity Costs

Continuous Power Output	KWH/Year	Cost/Year*	Cost/25 Years*
23	201,000	$12,400	$309,500
37	324,000	20,000	499,400
47	412,000	23,700	593,600
54	473,000	29,100	729,900
85	745,000	43,000	1,075,900

*Assuming a 4% increase beyond inflation.

The value of the recoverable waste heat also can be calculated using the same present value equation assumptions as before. The cost of the fuel oil which it will replace was $\$2.72/10^6$ BTU in 1974. Burned in furnaces with an estimated efficiency of 65 percent, the value is $\$4.18/10^6$ BTU actually used. The amount of recoverable heat from the diesel engines is 1350×10^6 BTU/year. The total value of this heat is 245,000 present value dollars or $9,800/year.

But this value cannot be added to the value of the methane because its use has already been included as a benefit in the Organic Wastes section as a source of heat for the digester, the support buildings, and the algae pond.

Conclusions

Of the five possible sources for electrical power generation at Marlboro College (hydroelectric, wind conversion, solar cells, and wood and methane combustion), only methane is economically available in sufficient quantities to supply the main campus demand. However, wind speed and potential site surveys should be conducted in the immediate vicinity of the college.

Under present conditions, the anaerobic digestion-diesel generation combination is a highly complementary arrangement. The digester provides fuel to the engines, and the diesels provide the necessary heating for the sludge tank, buildings, and algae pond that otherwise would have to come from oil or some other source of heat.

Fuel Cells

It would seem that any town or city has the raw material to supply a large portion of its non-industrial power needs, and at the same time can eliminate its sewage in a far more efficient manner. At the other end of the scale, it might soon become possible to have self-powered houses with individual digesters. But these systems would be best equipped with fuel cells instead of generators, thus eliminating the noisy, relatively inefficient combustion engine from the chain. But fuel cells at present are far too short lived and expensive for serious consideration. Pratt and Whitney quotes a figure of about $3,000/KW of installed power for their fuel cell system. When the cost becomes competitive with diesel generation, the college should probably switch to fuel cells.

Economics

The economics of the anaerobic digestion-diesel generation system are summarized in Table 21. The total capital and maintenance costs over 25 years are $260,000 or $10,400/year. It is expected that this system will provide 54 KW continuous power. If, as is expected, the college uses a constant 47 KW (it now uses 37 KW), the cost of commercial electricity would be $593,600 over 25 years or $23,700/year.

The cost of this electricity was calculated using the present value equation (Equation 6a, Solar Energy section) with the following assumptions: first, interest rates and the rate of inflation will be roughly equivalent, and second, the cost of commercial electricity will increase at a rate of 4 percent above inflation. This is believed to be a conservative estimation, at least for the present, since electricity rates have risen between 25 and 65 percent in Vermont in recent months.

This same 4 percent cost increase has also been applied to the diesel fuel, but because this cost is less than 30 percent of the yearly operating and maintenance costs of this system, a change in the 4 percent figure would have much less effect on the anaerobic digestion-diesel generation system than on the cost of commerical electricity.

Standby Electricity System

Because of the problems associated with synchronization, the college could not use commercial and on-campus generated electricity at the same time. And in the event of digester system failure, the electric company would not allow a switch-over from 0 to possibly as much as 100 KW peak demand. Thus, the college must have some alternate means of generating electricity in the absence of methane. Fortunately, the dual-fuel diesels can be modified in about an hour to burn diesel fuel alone.

There are three major reasons for installing three 40 KW generators as opposed to one larger unit. First, the diesel generator systems operate most efficiently when running near capacity. Second, the life of each generator will be increased by not having to run continuously as would a single large generator. Third, when an engine is down for repairs or over-haul, there will still be 80 KW generating capacity.

IX WATER POWER

The Stream

According to the United States Geological Survey map of the Marlboro area (Figure 17), Pond Brook flows out of South Pond at an elevation of about 1650 feet above sea level, and about one mile downstream flows past "Mumford House" at an elevation of about 1570 feet. The brook then descends rapidly for about one mile, passing the Halifax town line (elevation: 1340) and joining the Green River about one mile further on at an elevation of 1220 feet. Dropping 230 feet in elevation from just above Mumford House to a short distance below the Halifax town line, Pond Brook is almost continuously bounded on one side or the other by Marlboro College property. Although there are no other continuously flowing streams that join the brook within this reach, the volume of the water flowing in the brook slowly increases as it descends.

Historically, Pond Brook has been used to develop water power for various uses. The two members of the Mather family who built Mumford House had a canal built from South Pond to Pond Brook which entered the brook about 100 yeards below the house. Below the lower end of the canal they constructed a dam across the brook and there, at successive periods during the late 1700's, built seven mills of various types. The power for those mills was provided by the water. Some remains of this water power development can still be seen (56).

In more recent times, a concrete dam was built across Pond Brook near Mumford House, about 100 feet upstream from the current South Road bridge over the brook. The water level in South Pond was regulated to provide water power at this mill site and photographs show one effect of this on the pond: long mudbanks in the late summer. The concrete dam was destroyed by blasting some fifteen years ago, primarily because the dam was gradually failing with age and attendant silting, and because the beaver dams at the outlet of South Pond were periodically blasted, causing great surges of water to flow against and over the dam, threatening the road bridge below it as well as property downstream. Most of the pieces of the blasted dam remain at this site.

So far as it can be determined, the flow of water in Pond Brook has never yet been used to generate electricity. Thus, the primary question to be answered is:what potential power development is available in the one mile reach of Pond Brook relatively accessible to the college?

Water Power

The amount of useful work available from a given volume of water is primarily determined by three energy components:

potential energy--height above some given base point; kinetic energy--velocity offlow; and pressure energy (57). By reducing the potential energy component of the water through a water motor, with minimal production of heat through friction and turbulence, a large proportion of this energy can be converted into usable mechanical energy. This mechanical energy can be used to generate electric power. The amount of power available at any given site is limited by the head that can be developed and the rate of flow of the water as expressed in Equation 11 (57,58,59).

$$HP = \frac{62.4 \times Q \times H}{33{,}000} \tag{11}$$

where, Q is the rate of flow of the water in cubic feet/minute
H is the head in feet
62.4 is the mass in pounds of one cubic foot of water
33,000 is the number of foot-pounds/minute in one horsepower (60)

To convert horsepower into kilowatts the figure must be multiplied by 0.746. To determine how much power is actually obtainable, this figure must be multiplied by the overall efficiency of the installation used to generate the power.

With such a relatively long reach of stream to work with, many different engineering plans could be designed, developing different heads. For example, the greatest possible head might be developed by running a flume (open channel) out along the side of the stream valley. Obeying the hydraulics of open channels, the flume can be built on a very slight gradient while the brook drops at a much steeper rate. At the desired point the flume could become a penstock (closed channel) and run straight down the steep valley side to the brook again, developing a head of over 100 feet. The cost of such a system, however, makes it economically prohibitive, and its potential for ecological disruption of the brook is great.

Much of the lower stream reach under consideration is too remote from the college buildings to be of any foreseeable practical use for power production, because electrical generation from these points would involve large transmission losses and the costs of transmission lines would be much too great. Any water power development is likely to be associated with a dam for several reasons, including increasing the available head. This again rules out the lower reaches of the stream for the sheer size of the dam required at any of the possible sites, plus the added expense of trucking materials a considerable distance from the main road, would make such development much too expensive.

Dam Siting

The pondage behind a dam is important to a water power installation for several reasons. First, it tends to even out variations in water flow, which is essential for maintaining a constant head. Second, it allows short-term operation using water flows greater than the current flow in the stream. Third, it acts as a settling basin to remove silt and debris from the water, increasing the expected lifetime of the components of the water power installation.

The best dam sites are places where the greatest useful head can be developed and where dams can be made as small as possible and still impound the largest volume of water (60). Such sites are in the same area as those that have been used before, from the remains of the concrete dam right by Mumford House down to the site of the Old Mather Mills. This part of the Pond Brook reach also happens to be the closest of all to the buildings on campus. While still remote from the main campus, these sites are in close proximity to Mumford House and the Mumford Cottages, for which nothing else is being planned to contribute to their energy self-sufficiency. Because of the close proximity of South Road to the sites, transportation costs in development construction would be at a minimum.

Available Power

Head

With the use of transit, level, and stadia rod, the developable head was measured at three sites in this area. Using the remains of the concrete dam as a guide, a head of forteen feet could be easily developed there. A smaller head than this, one of about ten feet, is all that could be easily developed at the site of the old Mathers Mills. The best head might be developed by using the spot where the South Road currently crosses Pond Brook. Building a dam there, perhaps putting the road over the top of the dam, could result in a head of over twenty feet. There is also the possibility of using both the concrete dam site and the bridge site together to develop power at two locations.

Water Flow

The amount of water flowing in the brook is intimately related to the hydrological cycle (61,62). Only a relatively small portion of rainfall is to be found as runoff in streams in mountainous areas free of development. From fifty to seventy percent of rainfall is usually lost through evapotranspiration. Thus climate, season, topography, and the total amount and intensity of rainfall largely determine the availability of stream flow for power production.

There are two primary methods of measuring water flow in a small stream such as Pond Brook: the float method and the weir method (60,63,64,65). The part of the stream reach under consideration particularly lent itself to the weir method. The weir was installed just upstream from the remains of the concrete dam and daily readings were taken through July and August, 1974.

Records from United States Weather Bureau stations in southern Vermont show that February and October are usually the months with least precipitation. However, the records of an amateur weather station within one mile of the weir site showed that August was the driest month. This, combined with the fact that evapotranspiration losses would be near maximum during this part of the year, would indicate that these records would determine the minimum rate of water flow in Pond Brook.

The night after the weir was installed, the largest and most intense single rainfall of the summer occurred. The flow rate was increased ten-fold the next day. Two days later another heavy rainfall occurred. At about this same time there was a disruption of the beaver dams at the outlet of South Pond into Pond Brook. It was reported that it took the beavers about two days to repair their dams, during which time the water level in South Pond dropped an estimated two inches (a sizeable volume of water). It is probable that the flow out of South Pond rather than the rainfall accounted for most of the ten-fold increase in flow rate, particularly in light of the relatively minor effects of two other sizeable rainfalls later in July.

Few conclusions can be drawn from flow data for the summer of one year. At least a minimum of five years of daily weir readings is required for any serious consideration of water-power projects. However, in order to give some perspective to the data from the summer of 1974 in relation to other summers, the rainfall at the neighboring amateur weather station was checked against previous summers. It was found that 1974 was not an exceptionally dry one and that precipitation did not vary appreciably from the average.

The rate of flow of water in this part of the Pond Brook reach seemed to attain a steady minimum of twenty cubic feet/minute. Given an average amount of precipitation as the fall season progressed, the flow rate in Pond Brook would be expected to increase, if only because of the natural reduction of evapotranspiration losses. Periodic weir readings from September through November did show increases in the flow rate, with the average being around thirty-eight cubic feet/minute. While this remains a rather small flow of water, it is almost a doubling of the minimum flow.

Using Equation 11, the minimum flow rate falling through the head at the concrete dam site (Site 1) theoretically contains about 0.53 HP, or 0.40 KW. Minimum flow falling through the possible head at the current South Road site (Site 2), assumed to be twenty-five feet, contains about 0.95 HP, or 0.71 KW.

In an effort to use the maximum possible head with the given minimum flow, a different theoretical development which might be optimal is hypothesized. Instead of using solely the artificial head created by a dam, this plan would be a "divided fall" layout. It uses both the artificial head of a dam at Site 1 and the natural head of the descending terrain to a point just below Site 2. Calling this plan Site 3, the increased distance involved creates friction losses [perhaps 5 percent (66)] that affect the amount of head that can be developed at this site. Assuming a forty-foot net head at Site 3, about 1.5 HP (1.1 KW) would be available. In considering various specific forms of water-power developments, the power that can be produced and the economics involved will be referred to the potentials of Sites 2 and 3.

It must be reemphasized that the above energy figures pertain only to the assumed minimum rate of flow which would be constantly available. Power produced from minimum flow is called primary power. Additional power, called secondary power, is available whenever the flow is greater than minimum. In many cases the minimum flow exists for only a short time during the year and the secondary power that can be produced is greater than all the primary power. To determine this power distribution for Pond Brook, its flow-duration curve must be determined. This requires at least one full year (preferably several years) of flow rate data. The curve is then determined by plotting the values of stream flow, in order of magnitude, against the percent of time these flows exist (58).

Harnessing Power

Mechanical energy is extracted from water falling through the head by means of water motors that can be generally classified into displacement, gravity, impulse, and reaction types. Each type has had a long history of development into its current forms. While examples of displacement (hydraulic ram) and gravity (overshot waterwheels) will be discussed in terms of their potential application to Pond Brook, only the impulse and reaction types have undergone development into the highly efficient hydraulic turbines used for hydroelectric generation (57, 58,66,67).

In contrast to impulse turbines which operate in the open air (with splash covers), a reaction turbine operates with its waterwheel submerged, receiving its driving force from the water flowing over the curved runner blades, producing the mechanical energy that rotates a shaft connected to the runner. For hydroelectric power, a generator is mounted on the drive shaft. To maintain constant shaft speeds with varying load, a governor mechanism is employed to regulate the flow of water into the turbine through a set of wicket gates. The two principal designs of reaction turbines are the Francis turbine and the more recently developed propeller turbine which is characterized by two types of runners: fixed blade and adjustable blade (the Kaplan runner).

The principal design of impulse turbines is the Pelton wheel. The driving force for the shaft is produced by a high velocity stream of water, focused by a high pressure nozzle, striking carefully designed buckets attached around the circumference of the turbine runner which converts almost all of the kinetic energy in the water into mechanical (rotary) energy. The governor for this type of turbine operates by controlling the flow of water through the nozzle. Considering the energy content of the water as it leaves the turbine, the Pelton impulse turbine, as well as the Francis and propeller reaction turbines, can achieve over ninety percent efficiency in energy conversion.

In general, propeller turbines are used with the lowest heads (less than 100 feet) and largest flows; Francis turbines with intermediate heads and flows; and impulse turbines with the highest heads (particularly more than 1,000 feet) and smaller flows. This is not a rigid classification since each type is fairly adaptable. The requirements of certain power projects can call for a specifically designed turbine within a range of head not usually associated with it. For example, impulse turbines are frequently used in medium and even low head installations with small horsepower ratings (58,66,67). This is a possibility for Pond Brook.

Reaction turbines in general must be designed with small running clearances to reduce leakage to a minimum. This aggravates the effects of silt and cavitation erosion of the runner. When the water carries a large silt burden, which is probably true of Pond Brook at certain periods of high flow, this can lead to fairly frequent repairs and plant down time. In contrast, the design of a Pelton turbine is simple, with no close running clearances and no leakage problems. While the parts that are attacked by erosion, particularly the buckets, must be carefully made and mounted, they can be made of materials more resistant to erosion than can a reaction turbine runner, and above all these parts are easily replaced (67).

Operation of reaction turbines at small partial gate openings (reduced rates of flow) produces efficiency problems. In addition to permissable ranges of head, there are permissable ranges of flow which vary with turbine design. Operation is preferably limited to 80 percent or greater efficiency (66). The Francis and fixed-blade propeller turbines cannot be operated much below 70 percent of rated capacity and still maintain 80 percent efficiency. Adjustable-blade propeller and Pelton impulse turbines can be operated at less than 25 percent of capacity with greater than 80 percent efficiency. Thus, the adaptability, efficiency, and ability to produce power depend upon the interaction of head and flow with the particular design of the turbine.

Electricity Generation

Currently, there is an important constraint on the production of alternating current from hydropower. To maintain a given frequency, the speed of the generator must be fixed. Thus, the turbine must be synchronized with the generator to which it is usually directly attached, which means that the turbine speed must be closely regulated. The frequency must usually be maintained between 59.5 and 60.5 cycles/second for normal functioning of appliances.

An expensive governor is used to control the speed of the turbine by regulating the flow of water. They are designed to hold the prime mover to a practically constant speed during all changes of load, but no governor can prevent momentary changes of speed (and frequency) with load changes (58). Since the frequency of hydroelectricity generated at small installations cannot be maintained within the narrow limits acceptable to utilities, the direct connection to their power lines would be impossible. But it should be mentioned that this problem may soon be solved by research on generators for wind energy conversion which maintain exact frequency by using utility lines to excite the generator field to fix the output frequency (68).

While much of this remains for future development, the availability of such a system for small power plant sites could have great impact. It could affect the synchronous speed constraints on turbine design and the constant speed constraints on the expensive governor design. And such a system, when reliably developed, would remove the chief technical argument against the direct connection of small generating plant lines to utility lines.

Economics

The amount of electricity available from Pond Brook will never significantly affect self-sufficiency at Marlboro College. The only justification for using hydropower would be to generate electricity during peak load hours. For peak shaving to be economically effective, the college would have to first convince the electric company to reduce the electric bill in proportion to the amount generated, since the utility does not monitor the peak.

It is difficult, if not impossible, to determine the economics of hydrogeneration without more accurate flow data. While the primary flow can be estimated fairly well, there is no way to determine the secondary flow without a lengthy survey which is not justified on the basis of what can be accomplished in the way of power output and what the potential is for ecological disruption (69,70).

And even if the flow could be determined, it seems unreasonable that even in the best of circumstances the amount of generated power could ever repay the capital investment. The cost of two concrete dams (the state and the college insurer would probably not allow earthen dams) at sites 2 and 3 would be about $38,000. The dams would include spillways to handle floods, flush gates to reduce silting, trashracks, and penstocks. This includes the cost of relocating South Road over the breast of the dam at Site 2.

A local electrical contractor gave an estimate of the cost of a transmission line from the sites to the Mumford Cottages. Using five poles and 1,000 feet of insulated wire of sufficient capacity to carry 120 volt, single-phase current with insignificant transmission losses, the installed cost would be about $3,500.

It is assumed that the two turbines will cost a total of $13,000. Thus, the total capital investment will be about $54,500.

Assuming that twice the minimum flow can be used to generate electricity, a usable energy of 36 KWH/day can be expected, or 13,100 KWH/year. At present commerical electricity costs, this is worth $486/year. Assuming a 4 percent increase in commercial electricity costs/year beyond inflation, it would take 44 years of hydroelectric operation to pay for the capital costs alone. Operation and maintenance costs will lengthen this time period substantially. Whether the hydroelectric plant will last this long appears academic.

Conclusions

It seems without doubt that with the heads and flows that can be developed, hydroelectric generation from Pond Brook cannot currently compete with commercial electricity. When the large capital expenditure required for this installation is compared with the insignificant contribution to energy self-sufficiency, and when it is realized that this installation is competing for the limited available capital, it becomes abundantly clear that hydroelectric power is a low priority for the college.

Along this section of Pond Brook under discussion, the college owns land on either one side or the other--but not both. To install a hydroelectric generating system, the college would either have to purchase the opposite stream bank (increasing capital expenditures) or obtain long-term leases with adjoining landowners.

And finally, there are serious environmental objections to using Pond Brook to generate power. While the impact of obstructions to fish migration could probably be alleviated with fish ladders (further capital expenditure), the impact of continual water level fluctuations on stream ecology could probably not be avoided.

However, if there were a need for power for a specific device that does not require electricity, an investigation should be conducted into the feasibility of providing that power with a mechanical device such as a waterwheel, probably of the type which were used historically on Pond Brook. A waterwheel does not require a large capital investment, is free of the necessity for synchronization, and is much less disruptive to stream ecology because it does not require a reservoir and does not interrupt stream flow.

X CONCLUSIONS

Introduction

The overall energy outlook for this country for the future, particularly the next ten years, includes rising energy prices, dependence on foreign energy sources with its attendant effect on the United States economy, and an uncertain availability of energy. For these reasons, attaining energy self-sufficiency is desirable.

Marlboro College can become energy self-sufficient. Rising energy costs alone justify this conclusion, but the additional possibility that the college might have to close for lack of heating oil or electricity affirms the necessity of converting to the use of alternate sources of energy.

Energy Conservation

Before installing an alternate energy system, an aggressive energy conservation program is necessary. If properly executed, such a program will allow the college to reduce heating demand by possibly 30 percent or more. The expected reduction in electrical consumption cannot be determined with much precision, but it seems that as much as 20 percent might be expected. The reduction in energy use will have approximately equal effects on the economics of both conventional and alternate energy systems.

Although there are several reasons for reducing consumption, the major reasons for the college are to reduce the size of the necessary alternate energy systems and therefore the capital expenditure, and to lessen the strain on available energy sources.

Sources of Energy

The energy sources considered in this study were wind, flowing water, organic wastes, solar radiation, and the college forest. The energy needs of the college were determined and systems were designed to meet that need using the optimum combination of available resources.

The major college uses for energy are heat (92%) and electricity (8%). Several potential methods were found for supplying these needs. For example, heat could be provided by collecting solar radiation or by burning wood. Electricity could be generated with wind conversion devices, solar cells, fuel cells, hydropower, wood combustion, or bio-gas combustion. Most of these were ruled out on economic grounds.

Wind

Wind power technology was determined to be too expensive for use at present. The cost of wind-generated electricity exceeds $0.10/KWH, or about three times greater than the present cost. However, the cost of wind-generated electricity may well drop sharply when the systems are mass produced.

Flowing Water

The water power resource at Marlboro College is dependent on one stream. It was found that it could be used only on a seasonal basis and that the maximum available power is only a tiny fraction of that needed by the college.

Organic Wastes

It would not be economical to pyrolyze organic wastes to make a fuel. But it was found that methane gas could be generated by anaerobically digesting organic wastes, sewage, and algae grown on the undigested sewage treatment wastes. The resulting gas will be combusted in a dual-fuel diesel to generate all of the electricity demand of the college. The waste heat of the diesel engines will be used to heat the digester, the support buildings, and the algae pond.

Solar Radiation

Although it appears that it will prove economical sometime in the next decade, it is at present uneconomical to generate electricity using solar radiation. But solar radiation can be used to provide heat. Because the size of the collector field, and thus the capital expenditure, increases greatly as the amount of heat supplied approaches 100 percent, in order to remain economical there is a need for some auxiliary heat.

The College Forest

Wood can be fermented to single cell protein, digested to methane gas, pyrolyzed to form other fuels, and combusted to provide heat directly. Because of technical and economic problems associated with the other processes, the available wood will be used as the auxiliary heat source.

The Heating System

It was found that the optimum heating system is one in which the wood provides 42 percent and the flat plate solar collectors provide 58 percent of the heat (assuming energy conservation of 30 percent). This requires the use of the 200 cords of wood available from the forest each year and a solar collector field with about 1.2 acres of surface area. Both sources will be coupled to a centralized hot water storage system of approximately 100,000 gallons.

The present value of this system is $360,000 over its expected 20 year life. Assuming a 4 percent yearly increase in prices beyond inflation, the present value of the oil heat for the next twenty years is $540,000. These figures exclude maintenance costs as it is assumed that they are the same for both systems. The present value figure for the oil heat does not include system replacement costs which might occur over the next twenty years. The economics of conventional oil heat and wood-solar system heat are compared in Table 22.

Electrical Generation

The anaerobic digestion-diesel generation system is likely to provide about 54 KW of continuous power, considerably more than the 37 KW the main campus now uses. But with the new theatre building and the aerated lagoon system or the anaerobic digestion system, this figure is expected to be closer to 47 KW.

The present value of the anaerobic digestion-diesel generation system over its 25 year lifetime is $260,000. Assuming a 4 percent yearly increase in prices beyond inflation, the present value of conventional electricity is $593,600. The economics of conventional electricity and the anaerobic digestion-diesel generation system are compared in Table 22.

Table 22. Cost Summary.

System	Capital Costs	Operating and Maintenance Costs	Total Costs
Oil Heat	*	$540,000**	$540,000
Solar Heat	$200,900	0**	$200,900
Wood Heat	$53,300	$105,800	$159,100
			$360,000
Utility Electricity	0	$593,600	$593,600
Aerobic Lagoons	$81,000	$84,500	$165,800
Landfill	0	$115,300***	$115,300
			$874,700
Anaerobic Digestion	$203,700	$167,300	$371,000
Diesel Generation	$50,000	$119,900	$169,900
			$540,900

** Maintenance costs are assumed to be equal and are neglected.
*** This is the difference between the present landfill cost and the cost with an anaerobic digestion system.
* No replacement costs are included for the present system.

There are many minor questions which this study did not answer, and these are left for further research. But, from the research which was carried out, the conclusion is inescapable: Marlboro College can become energy self-sufficient using the alternate sources of energy available on campus. Because of the steadily dwindling supply of conventional fuels, it is the strong recommendation of this group that an alternate energy system be constructed at Marlboro College.

XI APPENDIX 1

Equations Used for Calculations in the Solar Energy Section

<u>Equation 1</u>. Calculation of Solar Radiation Falling upon a Horizontal Surface (2).

$$R_t = K \left[\frac{(1 + 0.8s)(1 - 0.2t)}{\sqrt{h}}\right] \quad \text{cal/cm}^2\text{/day} \qquad (1)$$

where, $K = (\lambda N + \psi_{ij} \cos\phi)\ 10^2$
ϕ = latitude in degrees
$\lambda = 0.2/(1 + 0.1\phi)$ (the latitude factor)
N = mean length of the day during the month
ψ_{ij} = seasonal factor (available in reference 2)
$s = n/N$
n = mean hours of bright sunshine/day during a month
$t = r/M$
r = number of rainy days/month
M = number of days/month
h = mean humidity/day in the month

Except as noted, all variables above are available from local weather stations. The units were finally converted to BTU/ft^2/day.

<u>Equation 2</u>. Optimization of Tilt Angle (6).

$$H_{ot} = \frac{24}{\pi} I_{sc} [\cos(L - \beta) \cos\delta \sin\omega_s +$$

$$\omega_s \sin(L - \beta) \sin\delta] \qquad \text{if } \omega_s = \omega_s,$$

$$H_{ot} = \frac{24}{\pi} I_{sc} [\cos(L - \beta) \cos\delta \sin\omega_s +$$

$$\omega_{s'} \sin(L - \beta) \sin\delta] \qquad \text{if } \omega_{s'} = \omega_s$$

where, L = latitude
β = angle of tilt of collector from horizontal
δ = solar declination
ω_s = sunset hour angle

$\omega_{s'}$ = sunset hour angle on the tilted collector
$\omega_{s'}$ = arc cos$\omega_{s'}$ - tan(L - β) tanδ
H_{ot} = radiation on tilted surface
I_{sc} = solar constant (422 BTU/ft^2/hour)

Equation 3. Daily Radiation on an Inclined Surface (6).

$$\bar{I}_{Tt} = \bar{H} r_t \,(\cos\theta_t/\cos\theta_h)[1 - (r_d/r_t)(\bar{D}/\bar{H})] +$$

$$(\tfrac{1}{2})(1 + \cos\beta)(r_d/r_t)(\bar{D}/\bar{H})$$

where, $\bar{H}$ = monthly average daily total radiation on a horizontal surface (BTU/ft^2/hour)
$\bar{I}_{Tt}$ = long term average hourly radiation on a tilted surface (BTU/ft^2/hour)
θ_t = incidence angle on a tilted surface
θ_h = incidence angle on a horizontal surface
$\bar{D}$ = monthly average daily diffuse radiation on a horizontal surface (BTU/ft^2/hour)
β = angle of tilt of collector
r_d = $\bar{I}_{dh}/\bar{D}$
r_t = $\bar{I}_{Th}/\bar{H}$
$\bar{I}_{dh}$ = long term average hourly diffuse radiation on a horizontal surface
$\bar{I}_{Th}$ = long term average hourly total radiation on a horizontal surface

Values of r_d and r_t have been established and are available from reference 6.

Equation 4. Radiation Absorbed by Collector (7).

$$q_a = 0.98\,[F_e(1 - D)(1 - S)]\,I \qquad (4a)$$

where, D = dirt loss factor (0.98)
s = sidewall shading factor = 0.031/cosθ

$$F_e = F_c + a_1(1 - e^{-kl}) + a_2(1 - e^{-kl}) \qquad (4b)$$

where, $a_1 = 0.10$; a_2 0.44. These values are for two cover plates and an emissivity in the long wavelength range of 0.02. For other values, see Reference 7.

$$F_c = \alpha[(T_{12} + r^2T^2) + (1 - \alpha)\, r\alpha(T_{12} + r^2T^2)] \qquad (4c)$$

in which, e^{-kl} = transmission of cover material for visible light (Tedlar = 0.98).

α = absorptivity of the absorber plate

T = transmission for cover at incident angle i

$$T = e^{-kl}\,\frac{(1 - r)}{(1 + r)}$$

$$r = \tfrac{1}{2}\left[\frac{\sin^2(i - i')}{\sin^2(i + i')} + \frac{\tan^2(i - i')}{\tan^2(i + i')}\right] \qquad (4d)$$

where, i = incident angle

i'= refracted angle = arc $\sin\left(\frac{\sin i}{n}\right)$

n = refractive index of cover = 1.46 for Tedlar

$$T_{12} = e^{-2kl}\,\frac{(1 - r)}{(1 + 3r)}\ ;\quad e^{-2kl} = 0.9604 \text{ (Tedlar)} \qquad (4e)$$

The above equations were evaluated from sunrise to sunset for the sixteenth day of each month.

Equation 5. Collector Heat Loss (7).

$$U_L = U_{up} + U_{rear} + U_{edge}\,\frac{A_p}{A_c} \qquad (5a)$$

where, U_L = total heat loss from collector

U_{rear} = heat loss from rear of collector = 0.09143 BTU/ft^2/H

U_{edge} = heat loss through edge = 0.08 BTU/ft^2/hour

A_c = area of the absorbing plate

A_p = perimeter area of the collector

plastic (1)

plastic (2)

collector (c)

$$U_{up} = \frac{\tau^2}{1-\chi}\epsilon_c h_{r_{cs}} \quad \frac{t_c - t_s}{t_c - t_a} \quad +$$

$$\frac{1}{\dfrac{1}{h_{c2} + E_{c2}h_{r_{c2}}} + \dfrac{1}{h_{21} + E_{21}h_{r_{21}}} + \dfrac{1}{h_w + \epsilon_1 h_{r_{1s}}\left[\dfrac{t_1 - t_s}{t_1 - t_a}\right]}} \qquad (5b)$$

where, $h_w = 1 + 0.3V$ (wind coefficient; V = wind velocity)

$h_{xy} = C(t_x - t_y)^{\frac{1}{4}}$ (convection coefficient)

$hr_{xy} = \sigma(t_k^4 - t_y^4)/(t_x - t_y)$ (equivalent radiative factor)

$\sigma = 1.723 \times 10^{-9}$ BTU/ft^2/hour

$$E_{xy} = \frac{1}{\dfrac{1}{\epsilon_x} + \dfrac{1}{\epsilon_y} - 1} \qquad \text{(emissivity factor)}$$

$$t_s = t_a[0.55 + 0.33(p_w)^{\frac{1}{2}}]^{\frac{1}{4}} \quad \text{(from reference 8)} \qquad (5c)$$

where, p_w = partial pressure of water vapor

t_s = blackbody sky temperature

t_a = ambient air temperature

t_c = collector plate average temperature

t_1, t_2 = temperature of transparent covers

τ = transmittance of plastic for long wavelength radiation (0.3 for Tedlar)

χ = fraction of long wavelength radiation that is completely absorbed at first plastic cover (0.45 for Tedlar)

APPENDIX 2

Table 6. Compartment 1: Present and Future Stand Tables (5 year growth).

DBH* CLASS	(STEMS/ ACRE) PRESENT STAND	AVERAGE VOLUME/ STEM (CORDS)	% MOR- TALITY	MORTAL- ITY (STEMS/ ACRE)	SURVIVAL (STEMS/ ACRE)	DIAMETER GROWTH %	G/I	ACCESSION 0 CHANGE	ACCESSION 1 CLASS	FUTURE STAND (STEMS/ ACRE)
4.5	65.11	-	20	13.02	52.09	1.89	0.42	30.21	21.88	30.21
6	97.45	0.040	10	9.75	87.71	1.67	0.25	65.78	21.93	87.66
8	63.62	0.087	10	6.36	57.26	1.41	0.28	41.23	16.03	63.16
10	37.39	0.149	5	1.87	35.52	1.31	0.32	24.15	11.37	40.18
12	21.17	0.227	5	1.06	20.11	0.99	0.29	14.28	5.83	25.65
14	13.33	0.328	5	0.68	12.66	0.91	0.31	8.74	3.92	14.57
16	7.76	0.422	5	0.39	7.43	0.74	0.29	5.28	2.15	9.20
18	2.93	0.532	5	0.15	7.55	0.73	0.32	5.13	2.42	7.28
20	1.46	0.759	5	0.07	1.39	0.81	0.41	0.82	0.57	3.24
22	0.52	0.649	5	0.03	0.51	0.91	0.50	0.26	0.26	0.83
24+	1.22	1.510	10	0.12	1.09	-	-	1.22	-	1.48

*For explanations of columns, see Appendix 3.

Table 7. Compartment 2: Present and Future Stand Tables (5 year growth).

DBH* CLASS	PRESENT STAND (STEMS/ ACRE)	AVERAGE VOLUME/ STEM (CORDS)	% MOR- TALITY	MORTAL- ITY (STEMS/ ACRE)	SURVIVAL (STEMS/ ACRE)	DIAMETER GROWTH %	G/I	ACCESSION 0 CHANGE	ACCESSION 1 CLASS	FUTURE STAND (STEMS/ ACRE)
4.5	63.01	-	25	15.75	47.26	2.0	0.45	25.99	21.27	25.99
6	111.36	0.044	20	22.27	89.09	2.1	0.31	61.47	27.62	82.74
8	58.29	0.098	15	8.74	49.55	2.1	0.42	28.74	20.81	56.36
10	30.37	0.152	10	3.04	27.33	1.1	0.27	19.95	7.38	40.76
12	14.77	0.224	5	0.74	14.03	1.1	0.33	9.40	4.63	16.78
14	13.79	0.338	5	0.69	13.10	1.2	0.42	7.57	5.50	12.20
16	5.43	0.435	5	0.27	5.16	1.0	0.40	3.10	2.06	8.60
18	2.92	0.522	5	0.15	2.77	0.74	0.33	1.86	0.91	3.92
20	1.43	0.828	5	0.07	1.36	0.90	0.45	0.75	0.61	1.66
22	0.49	0.651	5	0.02	0.47	0.46	0.25	0.35	0.12	0.96
24+	0.41	1.971	5	0.02	0.37	0.82	-	0.37	-	0.49

*For explanations of columns, see Appendix 3.

Table 8. Compartment 3: Present and Future Stand Tables (5 year growth).

DBH* CLASS	PRESENT STAND (STEMS/ ACRE)	AVERAGE VOLUME/ STEM (CORDS)	% MOR- TALITY	MORTAL- ITY (STEMS/ ACRE)	SURVIVAL (STEMS/ ACRE)	DIAMETER GROWTH %	G/I	ACCESSION 0 CHANGE	ACCESSION 1 CLASS	FUTURE STAND (STEMS/ ACRE)
4.5	77.17	-	20	15.43	61.74	2.5	0.28	44.45	17.28	44.45
6	28.04	0.028	15	4.21	23.83	2.8	0.42	13.82	10.01	31.10
8	119.60	0.079	10	11.96	107.64	2.2	0.44	60.28	47.36	70.29
10	20.69	0.122	5	1.03	19.66	1.8	0.45	10.83	8.85	58.22
12	41.15	0.205	5	2.06	39.09	1.5	0.45	21.50	17.59	30.35
14	4.82	0.303	5	0.24	4.57	1.2	0.42	2.65	1.92	20.23
16	3.97	0.400	5	0.20	3.77	1.0	0.40	2.62	1.51	4.54
18	-	0.435	-	-	-	-	-	-	-	1.51
20	-	-	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-	-	-
24+	0.75	0.318	15	0.11	0.63	0.54	-	0.63	-	0.63

*For explanations of columns, see Appendix 3.

Table 9. Compartment 1: Present and Future Volumes, and Volume Growth (5 year period).

DBH** CLASS	PRESENT VOLUME*	FUTURE VOLUME*	MORTALITY VOLUME*
4.5	-	-	-
6	3.90	3.51	0.39
8	5.53	5.49	0.55
10	5.57	5.99	0.28
12	4.81	5.82	0.24
14	4.37	4.78	0.22
16	3.27	3.88	0.16
18	1.56	3.87	0.08
20	1.11	2.46	0.05
22	0.37	0.54	0.02
24+	1.84	2.23	0.18
TOTAL	32.33	38.60	2.17

* Cords/acre

**For explanations of columns, see Appendix 3.

$$\text{Volume growth/acre/year} = \frac{\text{Future Volume} - \text{Present Volume}}{5 \text{ years}}$$

$$= 1.25 \text{ cords/acre/year}$$

$$\text{Mortality Volume/acre/year} = \text{Mortality Volume/5 years}$$

$$= 0.43 \text{ cords/acre/year}$$

$$\text{Total yield/acre/year} = (1.25 + 0.43) \text{ cords/acre/year}$$

$$= 1.68 \text{ cords/acre/year}$$

Table 10. Compartment 2: Present and Future Volumes, and Volume Growth (5 year period).

DBH** CLASS	PRESENT VOLUME*	FUTURE VOLUME*	MORTALITY VOLUME*
4.5	-	-	-
6	4.90	3.64	0.98
8	5.71	5.52	0.86
10	4.62	6.20	0.46
12	3.31	3.75	0.17
14	4.66	4.12	0.23
16	2.36	3.74	0.12
18	1.52	2.05	0.08
20	1.18	1.37	0.06
22	0.32	0.63	0.01
24+	0.81	0.97	0.04
TOTAL	29.39	31.99	3.01

*Cords/acre

**For explanations of columns, see Appendix 3.

$$\text{Volume growth/acre/year} = \frac{\text{Future Volume} - \text{Present Volume}}{5 \text{ years}}$$

$$= 0.52 \text{ cords/acre/year}$$

$$\text{Mortality Volume/acre/year} = \text{Mortality Volume/5 years}$$

$$= 0.60 \text{ cords/acre/year}$$

$$\text{Total yield/acre/year} = (0.52 + 0.60) \text{ cords/acre/year}$$

$$= 1.12 \text{ cords/acre/year}$$

Table 11. Compartment 3: Present and Future Volumes, and Volume Growth (5 year period).

DBH** CLASS	PRESENT VOLUME*	FUTURE VOLUME*	MORTALITY VOLUME*
4.5	-	-	-
6	0.79	0.87	0.12
8	9.45	5.55	0.95
10	2.52	7.10	0.13
12	8.44	6.22	0.42
14	1.46	6.13	0.07
16	1.59	1.82	0.08
18	-	0.66	-
20	-	-	-
22	-	-	-
24+	0.24	0.20	0.04
TOTAL	24.49	28.55	1.81

* Cords/acre

**For explanations of columns, see Appendix 3.

$$\text{Volume growth/acre/year} = \frac{\text{Future Volume} - \text{Present Volume}}{5 \text{ years}}$$

$$= 0.81 \text{ cords/acre/year}$$

Mortality Volume/acre/year = Mortality Volume/5 years

= 0.36 cords/acre/year

Total yield/acre/year = (0.81 + 0.36) cords/acre/year

= 1.17 cords/acre/year

APPENDIX 3

Construction of the Stand Tables (19)

Diameter Breast Height

The first DBH class has a range of only one inch, including those trees greater than 4 inches and less than or equal to 4.9 inches in diameter. The subsequent classes are in two inch increments, covering one full inch below and 0.9 inches above the indicated measure. All trees greater than 22.9 inches are placed in the 24 inch plus class.

Present Stand

This column is a simple stand table, expressing the number of trees per acre in each diameter class. The quantities were obtained through the use of the Patunoff inventory system.

Average Volume Per Stem

The figures in this column were calculated using a program run on the Hewlett Packard computer. The program was used to calculate the volume of every sample tree in the survey by the Gevoriantz formula. The program then sums the volumes of all the sample trees in each diameter class and keeps track of the number of samples in each class. Then it simply divides the sum of the volumes for each class by the number of trees in each class to arrive at an average volume for trees in each diameter class of the sample.

Percent Mortality

This is an attempt to account for those trees which will die during the five year period being projected. The quantities used are based on averages from data gathered elsewhere (19). The significance of the percent mortality is much reduced when fuel wood management is being considered since the dead wood is recovered in the harvest.

Mortality

This is simply the volume in dead wood expected to accumulate during the five year projection period, or percent mortality of the stems per acre figure.

Diameter Growth

The growth percent is calculated in a similar manner to the Patunoff inventory. It uses a modified formula, however, to account for diameter growth only, that is, 200/(R/I x DBH) instead of 400/(R/I x DBH). The diameter growth percent is then multiplied by 5 to cover the five year projection period.

G/I

The upward movement of trees into larger DBH classes is proportional to the ratio of the growth in inches over the DBH class increment. This ratio is known as the growth index, hence G/I, where G is the diameter growth in inches and I is the diameter class increment.

The interpretation of a G/I of 0.45, for example, is that 45% of the trees move up one DBH class and 55% remain in the original class. If the G/I is greater than unity, for instance 1.45, the interpretation is that 100% of the trees move up one class and 45% move up 2 classes.

Accession

This column lists the number of trees which have remained in the same class and the number which have moved up to a new class after the application of the G/I to the number of trees surviving after the five year projection period.

Future Stand

This column lists the number of trees expected to be found in each class after the projection period. It is simply calculated by adding the number of trees which have remained in each class to the number of trees moving up from the previous class.

Construction of the Volume Tables

Present, Future, and Mortality Volumes

These quantities are calculated by multiplying the appropriate stems per acre figure from Tables 6-8 by the appropriate volume per stem from the same table. The Future and Mortality Volumes are then divided by five to yield the average growth per year over the projection period.

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