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FEASIBILITY STUDY OF SOLAR ENERGY UTILIZATION IN MODULAR INTEGRATED UTILITY SYSTEMS

June 30, 1975

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER

Submitted by
ARTHUR D. LITTLE, INC.
Cambridge, Massachusetts 02140

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FINAL REPORT

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ABSTRACT

A study was performed to evaluate the feasibility and benefits of solar thermal energy systems on Integrated Utility Systems. The effort included the identification of potential system concepts, evaluation of hardware status and performance of weighted system evaluations to select promising system concepts deserving of further study.

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SUMMARY

A feasibility study was performed to evaluate applications of solar energy in Modular Integrated Utility Systems (MIUS). The study was performed over a period of approximately 3-1/2 months with the primary intent of evaluating the potential performance of solar thermal energy systems as elements of the major MIUS subsystems. Detailed interaction studies and design iterations of the entire MIUS incorporating the solar thermal energy system were beyond the scope of this effort.

By direction, a Village Complex MIUS located in the Washington, D. C. area was used as a baseline system in this study since extensive background information had been generated in past studies performed by the Urban Systems Project Office (USPO). The Village Complex is a community concept comprised of a Village Center and three surrounding neighborhoods. It should be noted that although the Village Complex was used as a baseline, the results of this study can easily be applied to many other MIUS concepts and individual applications in MIUS without loss of generality.

After reviewing available documentation, load and performance requirements were determined for the major subsystems and their elements, and preliminary solar thermal-energy concepts were defined and described by function, hardware requirements, temperature level, potential impact on MIUS and potential economic performance. A weighted evaluation was performed on all the concepts, considering such factors as technology status, potential economics, type of energy reduction (electrical or thermal), and ease of integration, with emphasis on land use requirements. Through this preliminary screening and evaluation, four of the initial solar application candidates were selected for further study. These surviving solar concepts were judged either to have promise or required additional detailed examinations.

The four major MIUS subsystems examined for solar energy applications were:

- Wastewater Management Subsystem
- Solid Waste Management Subsystem
- Power Generation Subsystem
- Heating, Ventilation and Air Conditioning (HVAC) Subsystem

Within the Wastewater Management Subsystem, solar sludge drying, (i.e., drying residual human waste via solar energy) and solar wastewater influent temperature stabilization were examined as means of reducing MIUS fuel consumption. Both of these concepts ultimately were judged unattractive through the use of the screening process. The major reasons for the poor showings include: a) extensive land area requirements where little suitable land is available, b) minor fuel savings, and c) unfavorable economics (large incremental capital investment charges per unit delivered

thermal energy). It is worth indicating that the unfavorable judgments on the above solar concepts were made assuming these solar applications did not have to compete against essentially free MIUS waste heat. The availability of sufficient waste heat clearly obviates these two solar concepts.

Solar solid-waste (trash) drying was considered in the Solid Waste Management Subsystem as a method of raising the heating value of the trash. Conceptually, this solar application would produce additional waste heat, which would help offset the summertime MIUS waste heat deficiency. However, solar solid-waste drying was also found to be unattractive for reasons similar to those outlined in the previous paragraph on the Wastewater Management Subsystem.

An examination of solar power generation concepts revealed three prime candidates for application in the MIUS: a) solar Rankine-cycle engine grid power production, b) dedicated solar Rankine-cycle engine water pumping, and c) solar and waste-heating bottoming Rankine-cycle engine grid power production. The evaluations of these concept applications revealed that the first two - pure solar grid power and solar shaft pumping power - were unattractive because of a combination of large land acreage requirements, low annual energy impact on the MIUS, and poor economics. The preliminary evaluation of the hybrid solar and waste-heat bottoming power production scheme revealed the need for further detailed studies of the relative contributions of the solar power, waste-heat bottoming power and diesel prime-mover power. A need was also sensed for a clarification of the primary economic variables which establish the economic feasibility of the concept. Thus, the hybrid solar and waste-heat bottoming Rankine-cycle engine concept was selected for additional investigation prior to making a final evaluation and recommendation.

For the purpose of concept definition and evaluation, the HVAC Subsystem was arbitrarily divided into low-density unit applications (single-family detached residences) and high-density unit applications (units tied into the MIUS piping network). The solar concepts which evolved for the low-density units included solar domestic hot-water production, solar hot-water and space heating (including the utilization of heat pumps, and combined solar heating and cooling. Furthermore, the above applications were considered for the low-density units taken individually and taken in small clusters. Primarily due to economics and MIUS energy impact, the preliminary evaluation and screening process resulted in favorable judgments for only solar domestic hot-water production and for solar hot water and space heating in the low-density units taken individually. As a result, a more detailed analysis and discussion of these concepts was prepared to clearly indicate the reasoning processes and methodology used in reaching the preliminary evaluation.

Within the high-density sector of the HVAC Subsystem, solar domestic hot-water production, solar hot water and space heating, and combined solar heating and cooling were considered for the townhouses (taken both individually and in small clusters) and for a centralized solar collector system integrated with the MIUS piping network. Because of the general

availability of MIUS waste heat, most of the above concepts were found to be economically unattractive. However, because of the summertime waste heat deficiency and the substantial auxiliary vapor-compression air conditioning electrical load, promise was indicated for centralized combined heating and cooling. Further detailed examination of the concept was thus undertaken to establish firmer predictions of technical and economic feasibility.

Solar desiccant dehumidification was another solar concept considered for application in both low and high-density units. The preliminary evaluations and screenings resulted in an unfavorable judgment for application of this concept in a centralized system or in residences - either single-family detached homes or townhouses. These judgments are based primarily on poor economic showing and technical impracticalities. Solar dehumidification did appear promising, however, in individual high-density units in the Village Complex, such as schools and hospitals. A final evaluation and recommendation on the concept was only possible, though, through the preparation of a more detailed study.

In summary, the solar concepts which survived the preliminary screening and evaluation stage, and which received a more detailed review, were:

- Combined Solar and Waste-Heat Bottoming Rankine-Cycle Engine Power Generation
- Solar Domestic Hot Water Production and Solar Hot Water and Space Heating in the Single-Family Detached Residences, including Heat Pump Utilization
- Central Combined Heating and Cooling for High-Density Units
- Solar Desiccant Dehumidification of Individual Buildings Connected to Central HVAC Subsystem.

From the extended analysis of the solar and waste-heat bottoming Rankine-cycle engine power generation concepts, the annual unit cost of energy was found to range from 3.7 to 5.2¢/KW-hr. Although these costs appear at first to be reasonable, it is to be noted that they reflect only a 5% solar contribution to annual energy need of the Village Complex MIUS. Annual unit costs of energy will increase significantly as the solar contribution is raised above the 5% level because of the concomitant decrease in low-cost energy from the waste-heat bottoming engine. For the advanced technology example illustrated in the report, the annual capital charge for the solar portion of the Rankine-cycle engine was about 5 times greater than the bottoming portion, while the annual solar energy contribution to the MIUS was about 5 times smaller. Consequently, the unit cost of solar energy was found to be approximately 14 times greater (16.8¢/Kwh vs. 1.2¢/Kwh) than the unit costs of waste-heat bottoming energy. Adding unfavorably to the high unit energy costs of solar generated power is the need for vast tracks of land for the solar collector panels. This land acreage was found to be incompatible with the Village Complex land structure, even with minor contributions to the annual MIUS energy load.

Solar domestic water heating in the single-family detached residences was judged to have the highest economic potential of the solar concepts studied. The efficiency of the solar energy collection system is high in this application because:

a. the load has favorable characteristics (steady, low in temperature)

b. conventional hot water heating accounts for approximately 18% of the annual MIUS electrical load in the Village Complex, thereby offering the potential for significant electrical energy savings, and

c. the technology required for solar water heating is less sophisticated than that required for other solar applications.

Solar water and space heating in single-family detached residences was also found to be very promising. This judgment was heavily weighted by the conventional heat-pump space heating system in the single-family residences, and by the annual load which accounts for about 15% of the MIUS annual electrical energy (and about 58% of the MIUS winter electrical energy.)

Several solar heat-pump system arrangements were examined, and the impact of design tradeoffs on cost-effectiveness (to the consumer) was analyzed. It was found that a system arrangement with an air-to-air heat pump operating as an independent auxiliary unit to the solar system will yield a lower net operating cost than can be achieved by a system arrangement with a water-to-air heat pump integrated with the solar storage tank.

The impact of solar heat-pump systems on the MIUS electrical load profile was also identified. In addition, heat-pump arrangements that could facilitate load management were discussed. However, the determination of the optimum MIUS load management heat-pump arrangement required additional analyses beyond the scope of the present investigation.

The central station solar collection concept for high density applications was not found to be attractive in the near term. The major reasons for this conclusion were marginal economics for central absorption chilling, and a requirement for a deficit in MIUS high temperature waste heat.

Solar dehumidification with desiccant systems in individual, high-density systems was found to have great promise in buildings that have high latent heat loads and where cooling is required year round. An additional result of the extended analysis is that the systems and

required collector areas will be significantly smaller than required for cooling via solar-activated absorption machines. Furthermore, desiccant systems have a potential for activation at lower temperatures than required for absorption cooling.

Solar desiccant dehumidification can benefit the MIUS by reducing the requirements for central chilled water, with the largest impact being the reduction of electrical energy required for the central, auxiliary vapor-compression chillers. Hence, the cost effectiveness of solar desiccant dehumidification is dependent on the requirement for a deficiency in MIUS high-temperature waste heat. Technology development of desiccant systems was found to be very active. It was concluded that designs evolving for solar space-conditioning applications may have considerably different parameters and configurations than those heretofore used. Also, the design, sizing, and economics of solar desiccant systems will be strongly dependent on climatic location and building type. For larger buildings centrally supplied with hot and chilled water, solar desiccant dehumidification might be cost competitive, depending on the cost/benefits which might be associated with reduction in central system capacity. Even if not cost competitive in solar installations, desiccant systems may have advantages over absorption air conditioning that merit their use when activated by MIUS central hot water.

In considering non-technical issues such as public acceptance, architectural integration and institutional constraints, attention was directed to characteristics of solar energy peculiar to implementation in the MIUS. From this work, two key issues were identified: 1) economic competitiveness and 2) allocation of land usage. These issues placed constraints on the types of solar applications feasible for integration with the MIUS, and were heavily weighted in the systems analyses.

RECOMMENDATIONS

Recommendations for continued activities are outlined below. The emphasis is on situations that are specific to the needs and applications of MIUS.

1) Solar heat-pump systems capable of providing both energy conservation and load management in the MIUS should be developed. A system definition study should be carried out to determine the most cost-effective solar heat-pump system from the standpoint of both the consumer and the MIUS, taking into consideration the influence of system design on the electrical load profile. It is further recommended that integration of the defined solar heat-pump systems into the MIUS Integration and Subsystems Test Bed (MIST) be accomplished, and experiments carroed pit to validate the potential for cost-effective solar heating and load management.

2) Further study should be given to use of desiccants for dehumidification in MIUS. The technology developed to date has tended to be very specific and application-oriented, and is now undergoing a technology explosion in response to interest in solar energy and other

energy conservation techniques. In addition to solar energy dehumidification applications, desiccant systems may have advantages over absorption air conditioning that merit their use when activated by MIUS central hot water.

3) Further study should be given to the use of Waste-Heat Rankine-cycle Bottoming Power Generation because of the potentially favorable economics identified in this study.

1.0 INTRODUCTION

1.1 General

The potential of solar energy, as an inexhaustible, widely available, clean alternative source of energy is receiving renewed recognition in view of the Nation's current concern with energy availability and cost. It is an inescapable fact that all natural resources are becoming increasingly scarce and more expensive. Therefore, efforts to develop renewable energy sources--first to supplement non-renewable energy sources and eventually, when they have been exhausted, to replace them--have recently been intensified, focusing on effective application of solar energy.

The recent recognition by government and industry of the consequences of wasteful uses of energy and the related environmental impacts has led to a new interest in the use of solar energy for heating and cooling of buildings, shown by conclusions of an NSF/NASA solar energy panel [1*] and recent government legislation [2,3]. Figure 1.1.1 summarizes factors governing the viability of solar energy systems.

The Urban Systems Project Office of NASA at the Johnson Space Center has conducted numerous studies of Modular Integrated Utility Systems (MIUS), which are self-contained total-energy systems designed to satisfy major utility needs--such as power generation; building space conditioning; water supply, and solid and water waste management--while minimizing consumption of fuels, water and other natural resources. Some important aspects of these studies involved the assessment of energy savings and cost competitiveness compared to conventional systems, an approach similar to that used to assess solar energy applications. Because of the similarity in objectives of MIUS and the utilization of solar energy, and because of the technical and economic potential being recognized for applications of solar energy for heating and cooling of buildings, it is of interest to explore applications of solar energy in Integrated Utility Systems. Figure 1.1.2 lists several special characteristics of MIUS concerning the use of solar energy.

---

* Cited References are listed in Section 5.0

FIGURE 1.1.1

FACTORS GOVERNING VIABILITY OF SOLAR ENERGY SYSTEMS

Application Load:

- Temperature Level of Load
- Variations in Load
- Magnitude of Load
- Reliability Requirement

Environment:

- Land Availability
- Climate and Locale
- Aesthetics

Equipment:

- Technology Status
- Performance Levels
- Maintenance Requirements
- Reliability

Economics:

- Equipment First Costs
- Life Cycle Costs
- Value of Competing Fuels
- Cost of Capital

Institutional Constraints

Social Acceptability

FIGURE 1.1.2

SPECIAL CHARACTERISTICS OF MIUS

CONCERNING SOLAR ENERGY

- Centralized Collectors may be Practical
- Potential to control interaction between utility and solar thermal systems
- Reasonable to consider focusing or tracking solar collectors
- Potential for non-space-conditioning applications
- Joint use of thermal storage possible

Exploration of the uses, advantages and potential of solar energy applications in a MIUS is the subject of this report. Although the emphasis will be on the economic and technical feasibility, the study also addresses the issues of environmental impact, public acceptance, and architectural interfaces of solar energy equipment. Of particular concern is the acceptability or viability of using vast tracts of open space within a community for solar energy collection equipment. The studies performed here were analyses aimed at displacing part of the conventional energy load with solar energy, but did not consider reconfiguring the MIUS into an optimum state of performance. Detailed MIUS interaction studies and design iterations were beyond the scope of the present effort. Thus, the impact on the conventional uses of waste heat were not considered when prime mover power production was lowered through solar energy utilization.

1.2 Community Concept

Integrated utility systems under study by NASA have ranged from 300 unit apartment complexes to satellite communities comprising neighborhoods, village centers and central business districts. This report describes a 3-1/2 month feasibility study of the impact and potential benefits of solar energy in the Village Complex MIUS (Shown schematically in Figure 1.2.1).

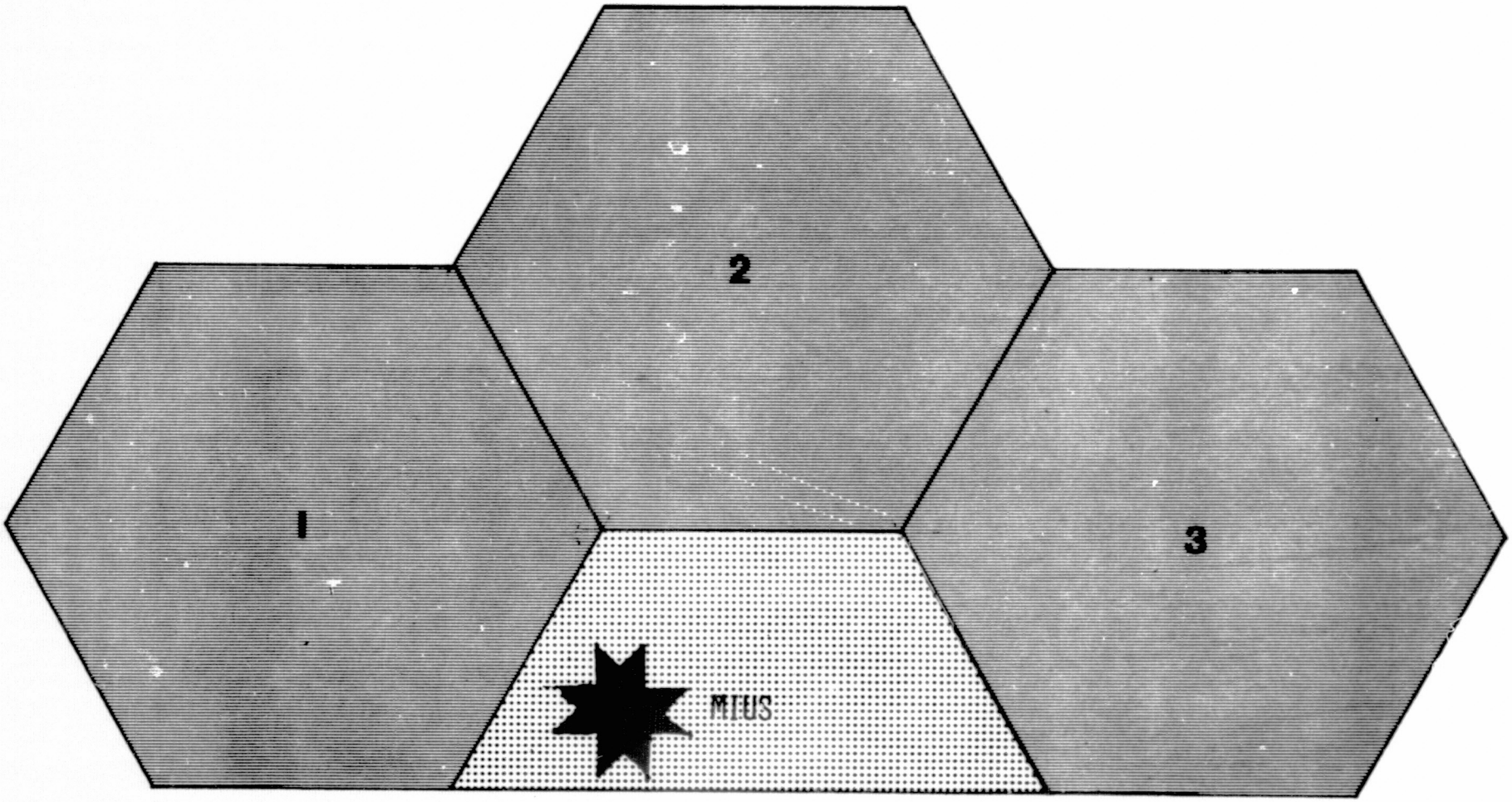
The Village Complex can be considered as a major element of a Community. In the community concept studied here, eight Village Complexes and one Central Business District constitute a Community.

The Village Complex MIUS was considered as a baseline for consideration, because most of the results and conclusions based on its use are equally applicable to other MIUS configurations. For example, many of the system concepts discussed in the report apply to individual buildings, general power generation, and central functions which exist in virtually all the MIUS configurations studied. The purpose of using A Village Complex MIUS as a baseline configuration was primarily from the standpoint of determining specific subsystem loads and requirements.

1.2.1. Village Complex

The Village Complex is based on three interlocking neighborhood units and a Village Center. The Village Center serves as the focal point of activity of the Village Complex. Here, there are office areas that allow decentralization from the Central Business District and encourage working within walking distance of housing. Local retail stores for approximately 15,000 people are provided. Included in the Village Complex, over and above housing in the Neighborhood, is a variety of housing types and densities. The expected population range for the Village Complex - the three Neighborhoods and Village Center - is 4,000 to 6,000 Families.

FIGURE 1.2.1



VILLAGE COMPLEX

(Form Ref. 4)

0 600 1200 2400 ft

MIUS FUNCTIONS

- POWER GENERATION
- HVAC
- POTABLE WATER TREATMENT
- SEWERAGE TREATMENT
- INCINERATION

NEIGHBORHOOD

VILLAGE CENTER

Arthur D Little Inc

1.2.2 Neighborhood

The Neighborhood (Shown in Figure 1.2.2) contains a variety of housing types and densities, including single family detached housing. These are clustered, with the majority around cul de sacs, to provide maximum usable open space. Townhouses and garden apartments are placed nearest the Village Center and in one section of the Neighborhood.

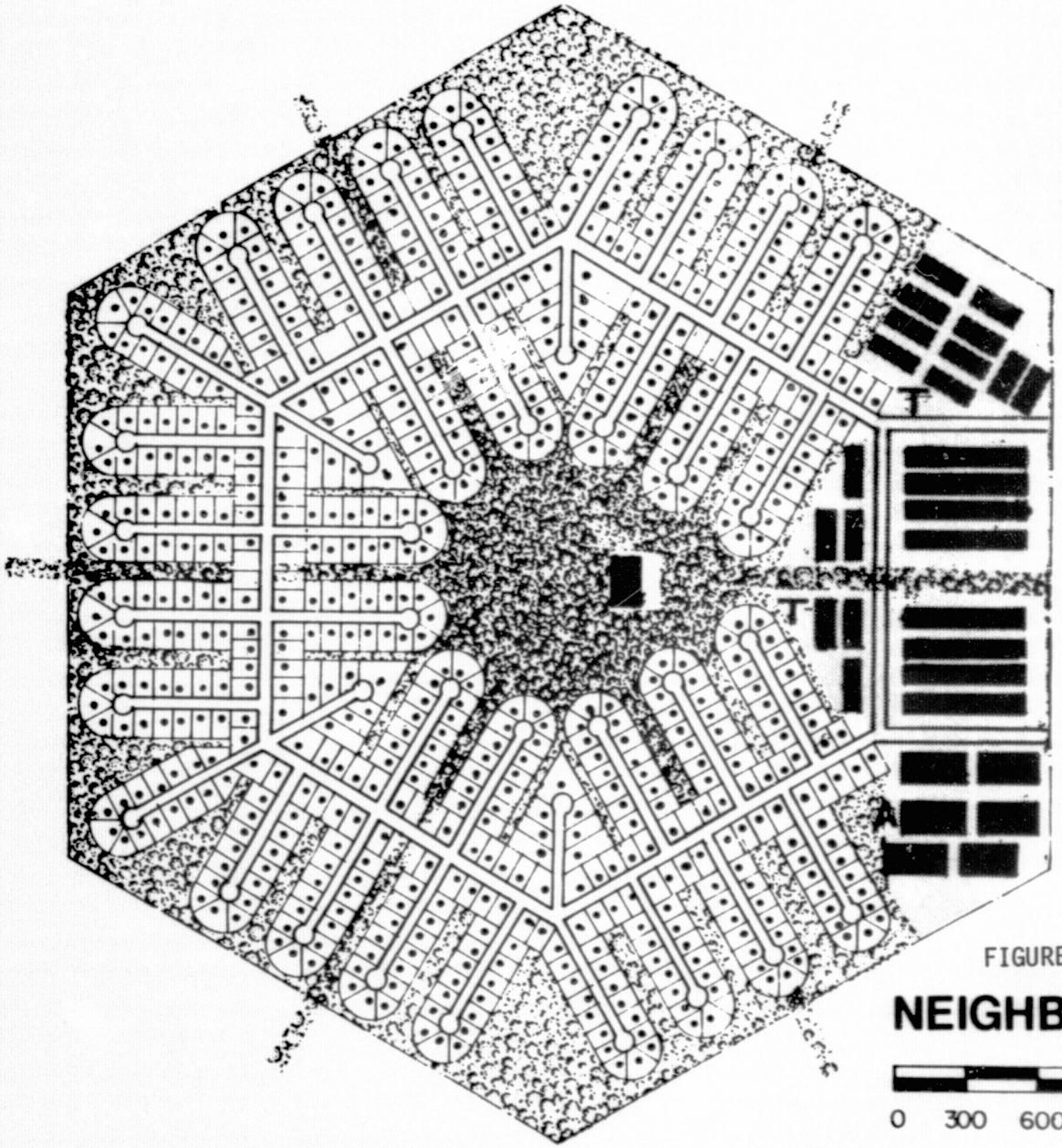
The proposed population levals of such Neighborhood designs range from 275 to 3,000 families. The number of families in Neighborhoods depends on the development schedule of the new community and usually is around 1,500 families. The model for the study has 1,361 families in a Neighborhood.

The major components of a Neighborhood are the elementary school (one in each Neighborhood), the open space with parks and recreation, pedestrian ways, vehicular avenues, and housing. The Neighborhood components modeled for this study are 713 single-family detached housing units. The multi-family units consist of 324 townhouse units and 324 garden apartment units. The average population of each Neighborhood after development is 5,000 people. The developed acreage per neighborhood is 332 acres. Open space takes up 33 acres (22 acres unstructured open space and 11 acre devoted to parks), with a total acreage in a Neighborhood of 365 acres.

1.2.3 Village Center

Figure 1.2.3 presents the layout of the Village Center. Secondary schools form the hub of the Village Center. The Village Center provides basic facilities and rudimentary services related to home life. Major recreation facilities are located in the Village Centers for community-wide participation with a different type of recreation in each Village Center.

The major components of a Village Center include: secondary schools, retail stores, offices, gasoline service stations, religious facilities, recreational facilities, high density housing and open space and park areas. The high density residential areas in the Village Center provide the potential resident of the community with an additional choice in housing types and densities. This housing is within easy reach of local retail, cultural and employment facilities without requiring use of public transportation. The proposed population range of the Village Center area is 300 to 400 families. The land area of the Village Center is 206 acres. Development within the center consumes 171 acres, leaving 35 acres (25 acres for park and recreation and 10 acres as unstructured open space).



LEGEND

A APARTMENT
S SCHOOL
T TOWNHOUSE
OPEN SPACE
• SINGLE FAMILY DETACHED

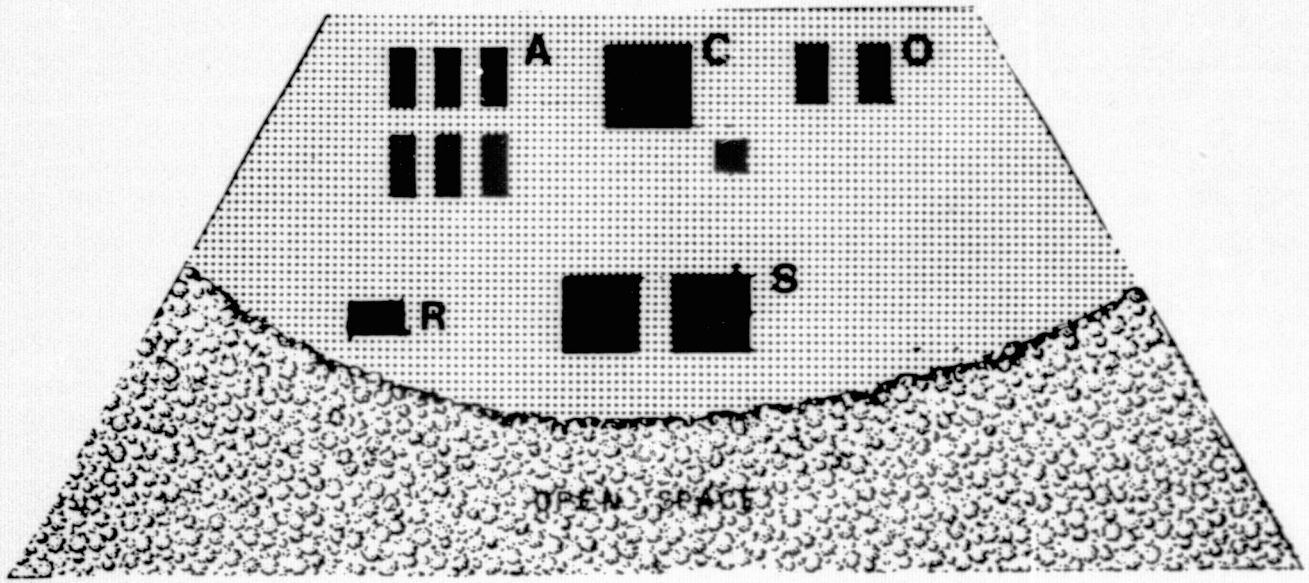
LAND USAGE:

332 Acres Developed
11 Acres Park
22 Acres Unstructured
365 Acres Total

FIGURE 1.2.2

NEIGHBORHOOD (Form Ref. 4)

0 300 600 1200 ft.



LAND USAGE:

171 Acres Developed
25 Acres Park
10 Acres Unstructured
206 Acres Total

LEGEND

A APARTMENTS
C COMMERCIAL
O OFFICE
R RECREATION CENTER
S SCHOOL
OPEN SPACE

FIGURE 1.2.3

VILLAGE CENTER (form Ref. 4)

0 300 600 1200 ft.

1.3 Description of the Village Complex MIUS

The Village Complex MIUS is designed to provide all the service requirements for the Village Center and three adjacent Neighborhoods. Figure 1.3.1 is a schematic of the Village Complex MIUS, while Figure 1.3.2 provides an annual energy balance. The power generation system consists of eight 4,415 KW diesel generators with both low-grade and high-grade heat recovery systems. The low-grade thermal energy is taken from the intercooler, lube oil, water jacket, and supplemented by the high-grade thermal energy in order to provide 200°F water for space heating and domestic hot water. This water is piped to the buildings in the Village Center and the higher density area of the Neighborhoods; the single-family detached buildings are all electric (space conditioning is provided by heat pumps).

The high-grade (250°F) thermal energy is generated by using low-pressure steam heat recovery units on the exhaust of each prime mover. The steam heater from this recovery unit is also tied into the heat recovery system of the incinerators. There are four 3,000 lb/hr incinerators used in the Village Complex MIUS in order to handle all the trash from the Village Center and three adjoining Neighborhoods. This low-pressure steam is used to drive the four absorption chillers which are used in the HVAC subsystem.

A chilled water distribution loop is routed to all the Village Center buildings plus the higher density areas of the Neighborhoods in order to satisfy the air conditioning requirements. The chilled water is generated by four 1,377-ton absorption chillers and four 1,073-ton electrically-driven vapor-compression chillers. Rather than using a cooling tower for extracting the heat from the chiller condenser water, a 360' x 162' duel-purpose pond is used. The pond cools the condenser water and also provides the necessary capacity for the Village Center and Neighborhood firefighting requirements.

Sewerage treatment is handled using a conventional biological system designed for a 1,675 mgpd capacity. Potable water is treated by using coagulation/flocculation, clarification, mixed media filter and disinfaction. This system has the same capacity as the sewerage system, 1,675 mgpd.

1.4 Review of Solar Collector Characteristics

Solar collectors will be discussed here because they are a major component, both in function and cost, of a solar thermal energy system. A solar collector is a surface (or composite surface) which, by virtue of its geometry or surface properties, absorbs solar energy and imparts this energy to a heat-transfer fluid that circulates through the collector. In order to operate at elevated temperatures the solar collector must serve as a heat trap and minimize heat loss from the absorbing surface.

FIGURE 1.3.1 System Schematic of the Village Complex MIUS (form Ref. 4)

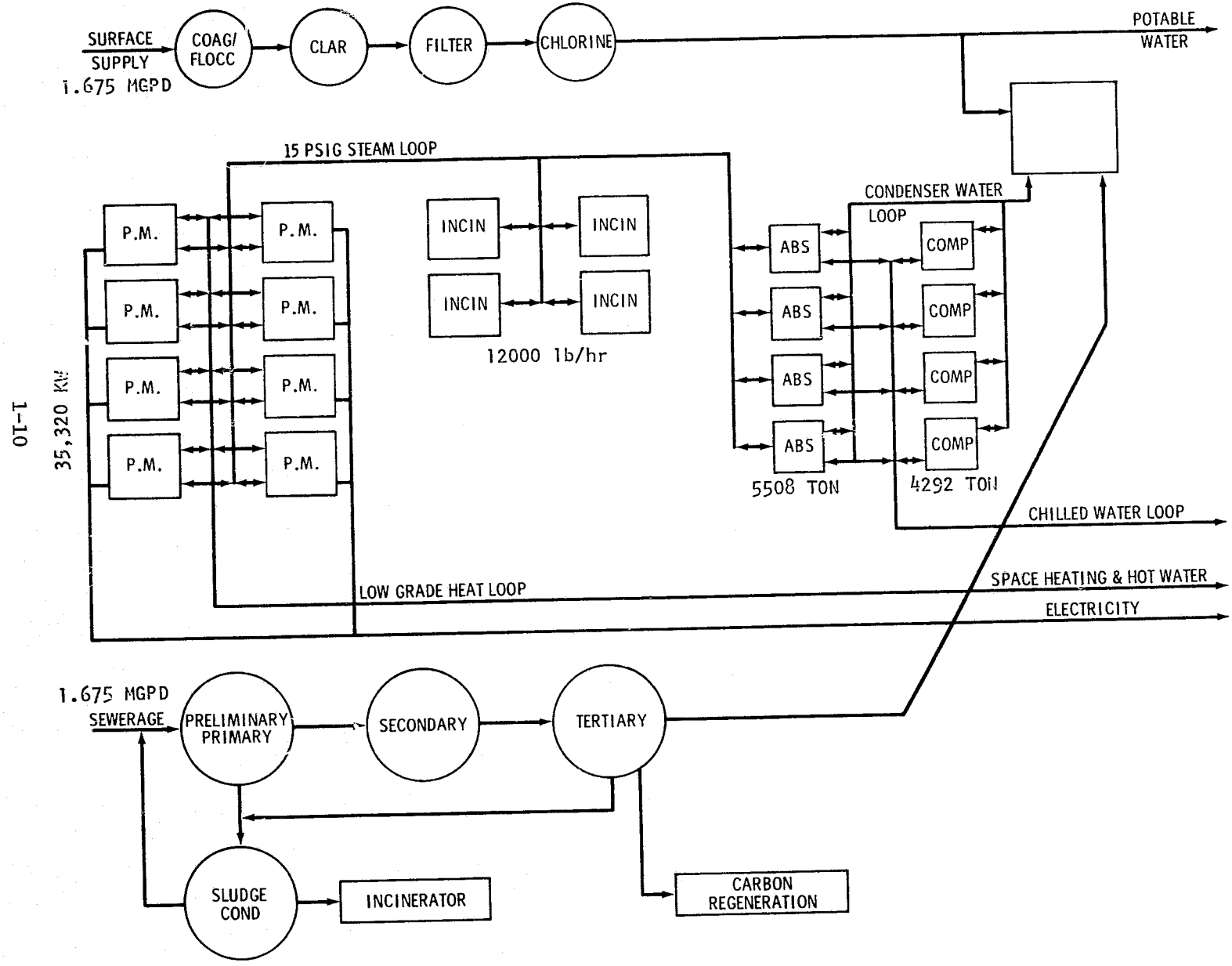
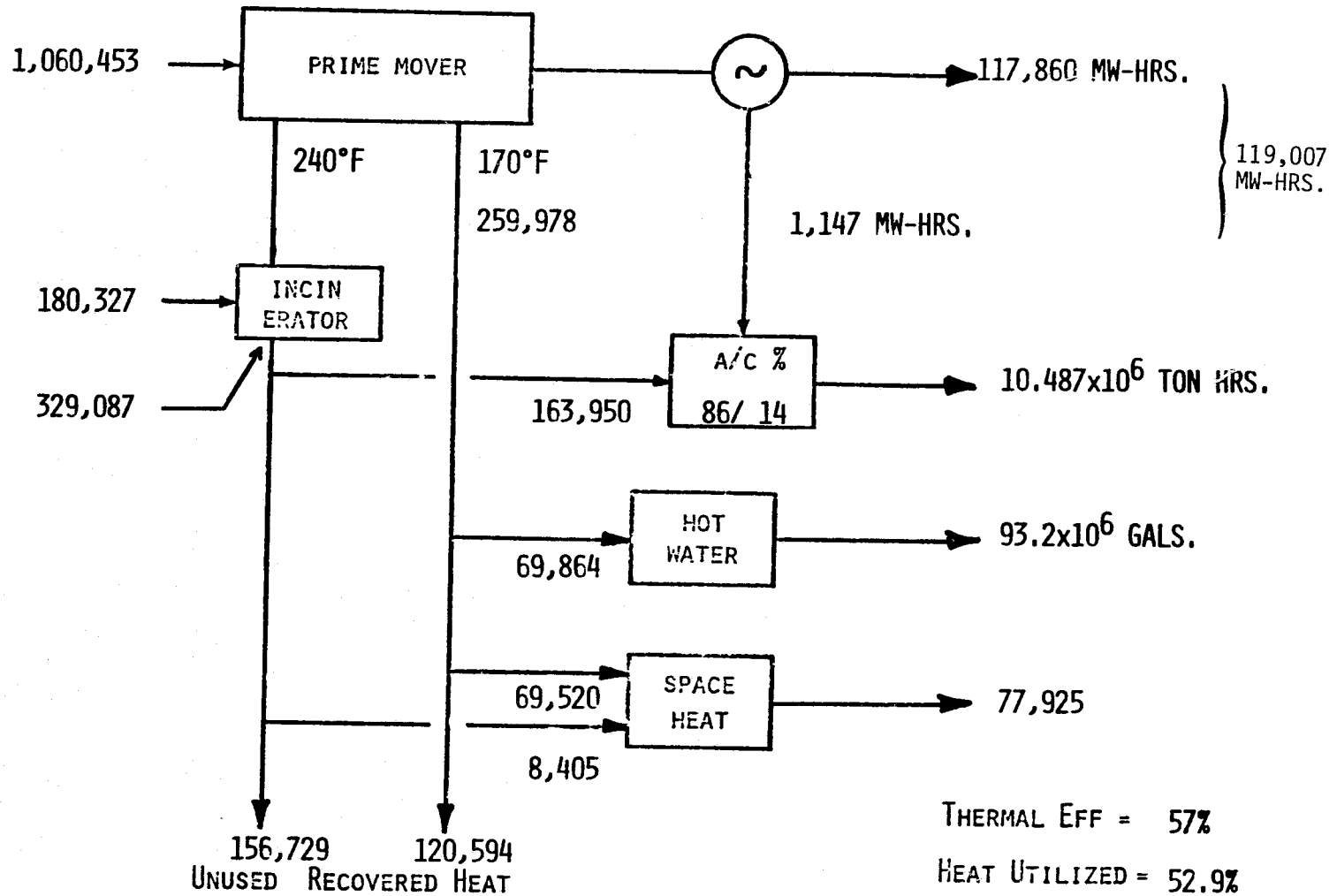


FIGURE 1.3.2

VILLAGE COMPLEX MIUS ANNUAL ENERGY UTILIZATION)form Ref. 4)



NOTE: Except where indicated, all numbers in millions of BTU's

The general collector design options include: selective transmission cover panes, which are transparent to solar radiation, but opaque -- or even reflective -- to re-radiated infra-red energy; selective absorbing surfaces which have high absorbance to solar radiation but do not radiate well in the infrared; suppression of convection and conduction heat losses; and the use of area ratio or concentration to reduce the heat loss area relative to the collection area. Because area ratio, or concentration, has the greatest impact on collector design and performance, solar collectors are typically classified in terms of the degree of concentration of incident solar energy.

High-concentration solar collectors employ optically precise focusing and must track the sun. This type of collector, which can achieve high collection efficiency at high temperatures, is a logical choice for solar power generation. However, the high concentration collector is effective only in direct (as opposed to diffuse) sunlight, and the cost and reliability of its tracking equipment and its focusing configuration make it impractical for solar climate control.

Low-concentration solar collectors do not require tracking and are effective where subjected to diffuse as well as to direct radiation. This type of collector is adequate for the temperatures required for solar heating and cooling (although cooling does require somewhat higher temperature performance and heating), and it is generally regarded as the best approach for solar climate control. The most common example of the low-concentration collector is the conventional flat-plate collector. Many novel versions of this basic collector design can be expected to be developed. In addition, other stationary collecting devices and techniques such as cylindrical collectors, collectors with partial concentration, and the use of reflecting surfaces to augment solar radiation received by a collector also fall into this classification.

A typical flat-plate solar collector, such as that shown in Figure 1.4.1, consists of an absorber (either blackened or selectively black to energy in the solar radiation spectrum) covered by one or more transparent panes. The cover pane(s) is relatively transparent to the incident solar radiation, but opaque to re-radiated energy from the absorber so that the collector assembly, like a greenhouse, serves to trap solar energy.

A solar collector operates most efficiently when absorber temperatures are not greatly in excess of ambient temperature and when the incident solar radiation is high. As the temperature difference between the absorber and ambient increases, heat loss increases, and the collector efficiency declines -- ultimately reaching zero efficiency when heat loss equals the heat absorbed. Moreover, at a given absorber temperature (or a given absorber - ambient T), efficiency falls off rapidly as the incident solar radiation decreases since, in this situation, the heat loss is constant while the heat input decreases.

Methods of improving solar collector efficiency generally are directed at reducing the convective, radiative, and conductive heat losses from the absorber plate without substantially reducing the solar energy transmitted to, and absorbed by, the absorber plate.

Figure 1.4.2 illustrates the performance of several low concentration solar collector designs, showing the effects of increasing the number of panes, utilizing selective surfaces, and convestion/conduction suppression by high vacuum--or other suppression techniques.

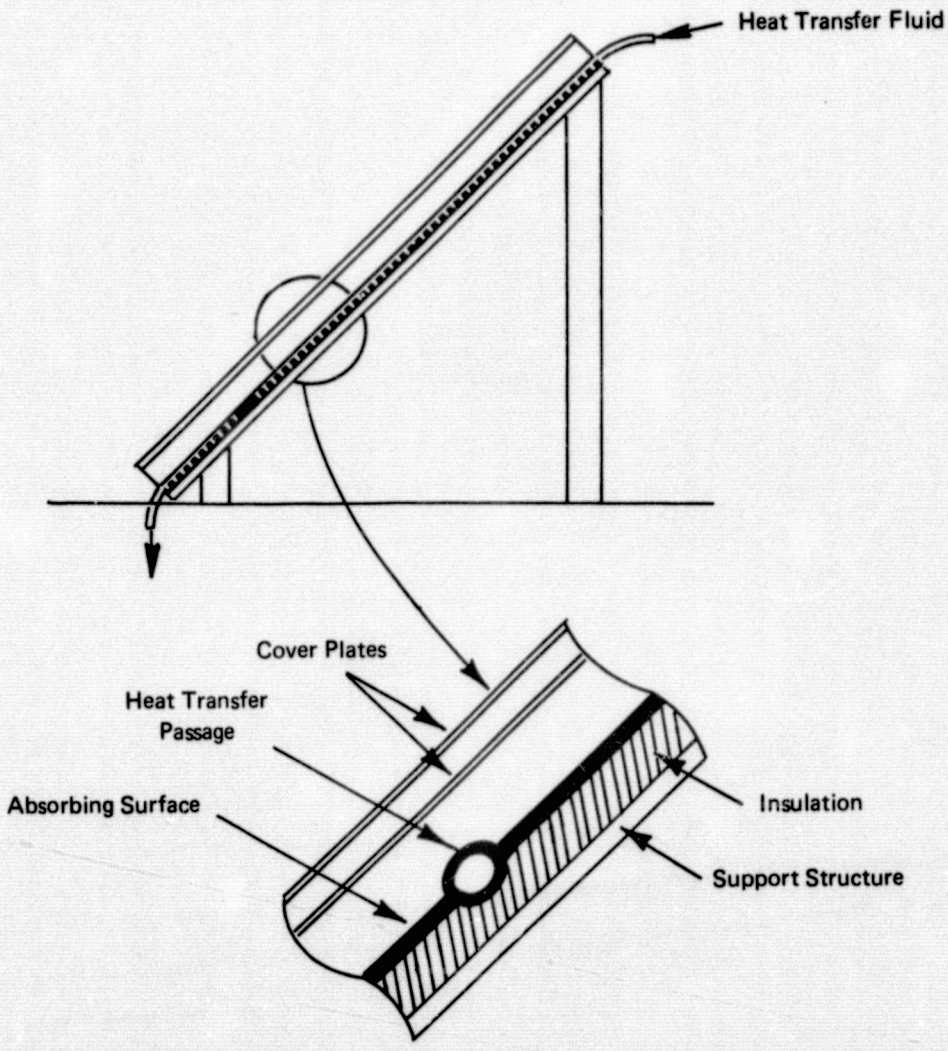
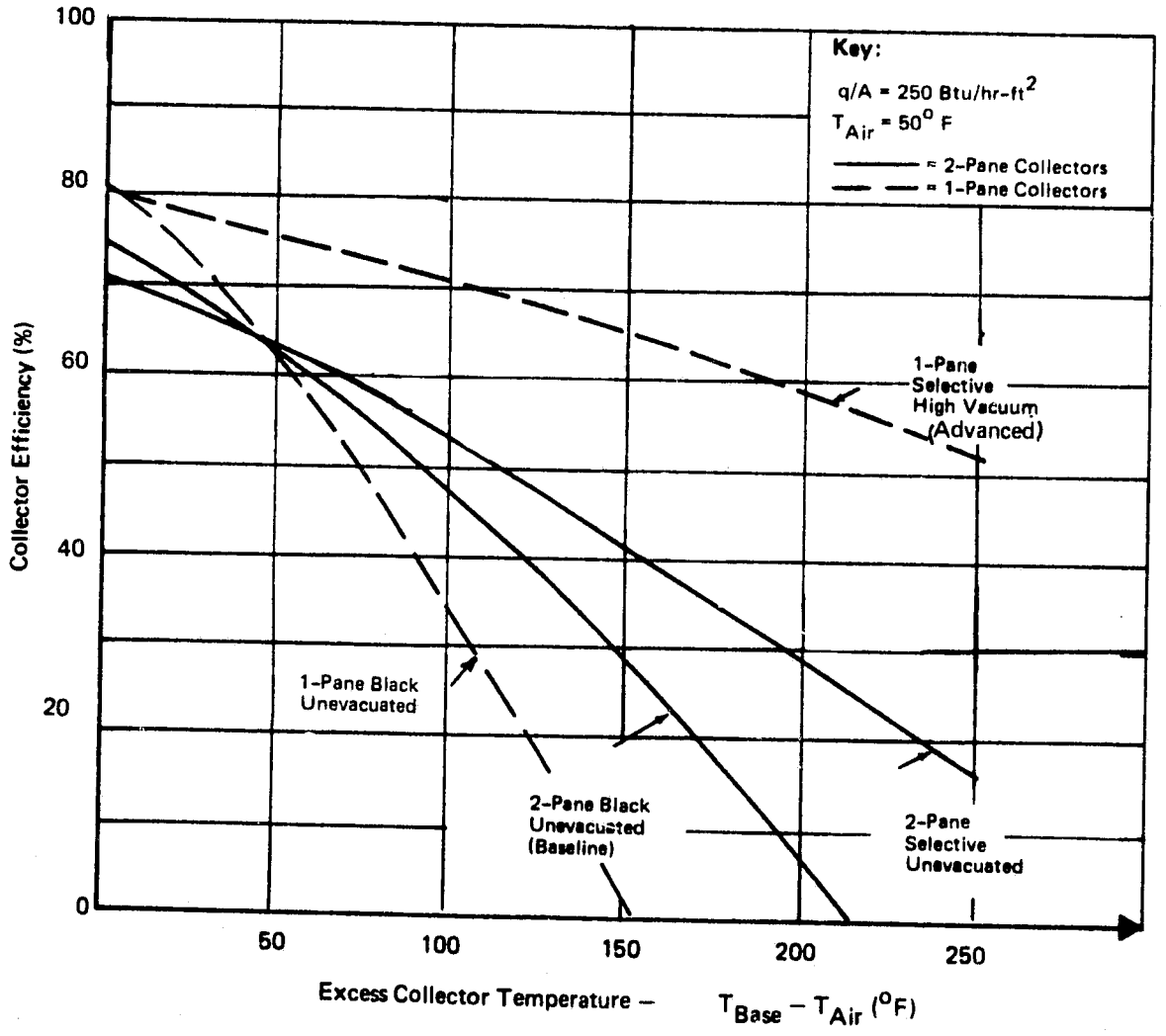


FIGURE 1.4.1 **FLAT PLATE SOLAR COLLECTOR**

FIGURE 1.4.2

COLLECTOR EFFICIENCY VS. EXCESS COLLECTOR TEMPERATURE



Source: Arthur D. Little, Inc. Computation

2.0 PROGRAM APPROACH

2.1 Methodology

An overall flow diagram depicting the program study approach is shown in Figure 2.1.1. Two important inputs to the study were documentation of previous efforts at the Urban Systems Project Office (USPO) relating to MIUS studies, and existing information at Arthur D. Little, Inc. (ADL) on solar energy systems. This ADL information is based on the results of more than 1000 computer runs analyzing the performance of solar climate control (SCC) systems in 11 different building types for nine different geographical regions in the United States. Much of this information has been presented in the form of correlation curves so that generalizations could be made to other operational conditions. We also utilized ADL informational resources on equipment availability and cost, which had been accumulated as a result of past and ongoing studies in solar energy applications.

Computer runs were made in the present study using existing ADL software (e.g., a "Computer Simulation Program for Solar Climate Control Systems") to refine performance predictions for specific solar energy concepts. However, program modifications to model the MIUS configuration, or to make use of an Energy Systems Optimization Program (ESOP) developed for NASA to be used for systems studies of integrated utility systems, were beyond the scope of the present study effort. Interactive computer modeling studies of both solar energy system concepts and the MIUS configuration would be an appropriate follow-on effort to the present study to refine the impact assessment and evaluation of promising systems that have been defined from the work described in this report.

After reviewing the MIUS documentation the thermal loads and energy requirements of the following major subsystems in the Village Complex MIUS were identified:

- Potable Water and Wastewater Management Subsystems, and
- Solid Waste Management Subsystem
- Power Generation Subsystem
- Heating, Ventilation and Air Conditioning Subsystem.

Following the characterization of the above subsystems loads, candidate solar energy concepts were identified. Next, a weighted system evaluation scoring form was constructed to screen the candidate solar energy concepts and determine those worthy of further detailed evaluation in this study, and/or for consideration in future efforts beyond this study. The weighted system evaluation procedure is illustrated in Table 2.1.1. In the procedure, a numerical rating of 0 to 5 was assigned to each of four key characteristics: 1) Availability of Equipment; 2) Potential Economics; 3) Energy Reduction, and 4) Ease of Integration.

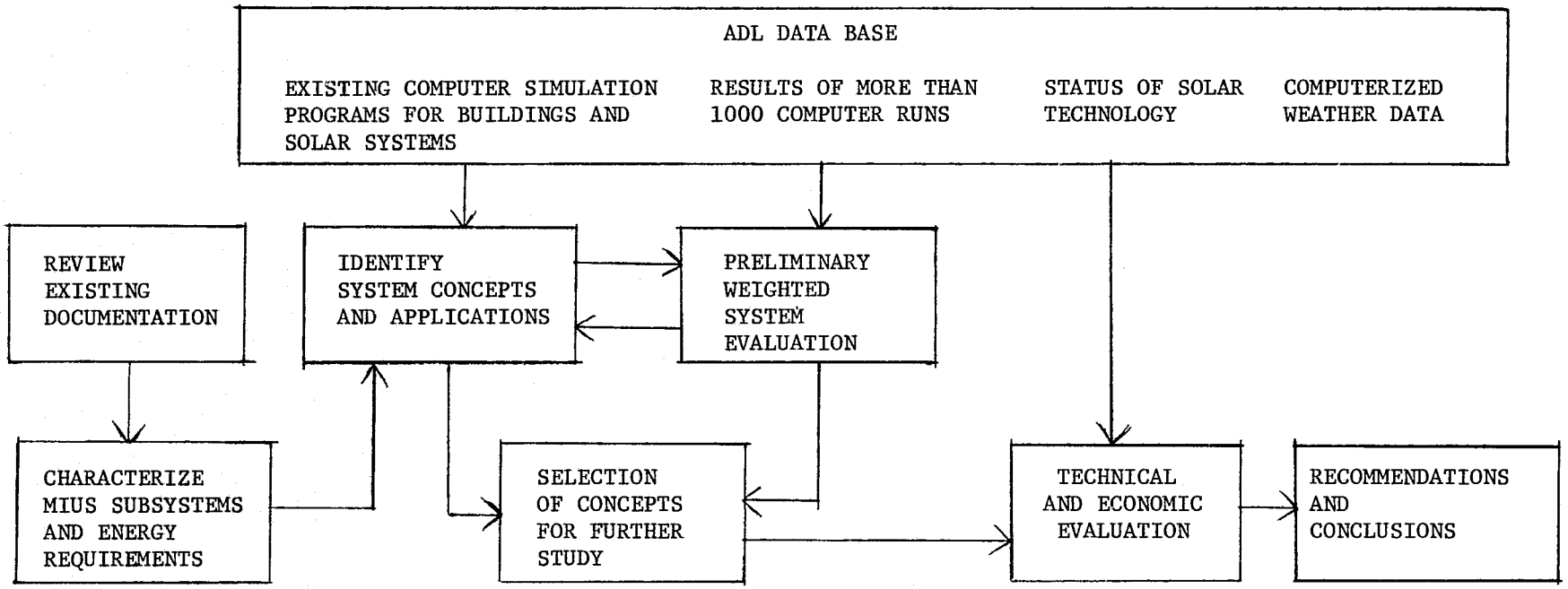


FIGURE 2.1.1 STUDY FLOW DIAGRAM

Each selected numerical rating was then multiplied by an appropriate weighting factor and the result summed to arrive at an overall score for the solar energy concept. We decided to display the scores given to each system characteristic as well as the overall score, so that it would be apparent what assumptions and information were employed so that an assessment could be made as to what changes would occur in the overall evaluation if different ratings were assigned.

The procedure represented in Table 2.1.1 shows that in the preliminary evaluation, potential economics and energy reduction were considered more important than equipment availability and ease of integration. Of course, sufficient land must be available for a solar concept to be viable, regardless of the economic incentive or fuel savings. Preference was given to concepts that resulted in an electrical energy reduction as compared to thermal energy reduction because:

- Electrical energy reductions directly lower the consumption of diesel fuel and reduce the size of the diesel prime movers.
- Energy balances and load characteristics of MIUS configurations examined to date have exhibited excesses of annual waste heat rather than having deficiencies. *

Later evaluations gave consideration not only to the type of energy reduction but also the magnitude of the reduction.

An important element in the consideration of ease of integration dealt with the allocation of land that may be necessary as sites for solar collector arrays. This is important in that some solar concepts are totally impractical in that more land would be required than would be available or desirable to devote to solar collector array structures.

2.2 General Assumptions and Bases of Evaluation

Much of the past work on MIUS applications has been based on the utilization of commercially available equipment and systems. Since solar energy represents an emerging technology without an established market, we were directed to consider equipment which could be available within a period of five years, although preference was given to equipment available within 2 years.

---

* It should be noted that it is possible to envision systems without excess waste heat, such as those with binary prime movers (i.e., with bottoming cycles) or with reduced base electrical loads that could result from the use of energy conserving building and usage practices.

TABLE 2.1.1 WEIGHTED EVALUATION PROCEDURE

Maximum
Total Score - 125

SYSTEM CHARACTERISTIC	RATING	WEIGHTING FACTOR
• AVAILABILITY OF EQUIPMENT		
0 - 2 years	3 - 5	5
3 - 5 years	1 - 2	
> 5 years	0	
• POTENTIAL ECONOMICS		
Expect to be competitive	3 - 5	10
Promising	1 - 2	
Not competitive	0	
• ENERGY REDUCTION		
Electrical	4 - 5	
Thermal	1 - 3	7
None	0	
• EASE OF INTEGRATION		
Convenient	4 - 5	3
Complex	1 - 3	
Impossible	0	

Some brief comments on solar equipment availability follow. This is not meant to be a review of solar technology, but rather background information to give the reader an appreciation of some of the considerations which entered into the characterization and evaluation of system concepts that are described in Chapter 3 of this report.

Figure 2.2.1 presents a graphical representation of our current estimate of the commercial availability of solar collectors and solar-related hardware, and was used as inputs to our solar concept evaluation effort. Figure 2.2.2 presents a matching of operational temperature ranges, generic types of solar collectors, and solar thermal energy applications. Photovoltaic devices are not expected to be available within the five-year time frame of interest. In Figure 2.2.1, "commercial availability" relates to equipment that will be manufactured and sold in the commercial marketplace, even though the costs at that time may not yet reflect economies achievable when a significant market exists and large quantities are produced.

Solar collector costs are an important aspect of the concept evaluations, because they represent a substantial fraction of the total solar system cost and because they introduce significant performance-cost trade-offs.

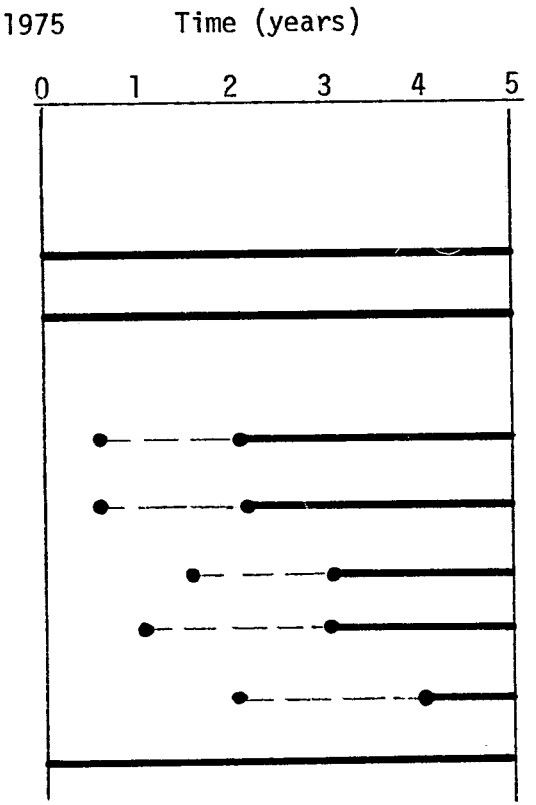
Figure 2.2.3 qualitatively represents the costs of solar collector subsystem components on the basis of dollars per square foot of solar collector. The top line in the figure represents the total system cost.

We have considered the costs of both current technology systems (baseline) and advanced technology systems. The solar collectors associated with these systems have been previously identified in Figure 1.4.2. As may be seen in Table 2.2.1, the mass produced, installed cost of a baseline (current technology) collector was assumed as $\$7/ft^2$, while an advanced technology collector was about $\$11/ft^2$. These costs were assumed insensitive to size. The total system costs do, however, vary considerably with size. As shown in Table 2.2.1, current technology systems were assumed to range in cost from $\$10/ft^2$ to $\$20/ft^2$ above the correspondingly sized current technology system.

Typical costs of conventional energy sources are depicted graphically in Figure 2.2.4. This figure is included primarily to serve as a guide to the general competitiveness of certain solar thermal energy concepts considered for MIUS. This will help in making judgments in the context of both MIUS and non-MIUS applications.

Figure 2.2.1
PROJECTED COMMERCIAL

AVAILABILITY OF SOLAR HARDWARE



1) SOLAR COLLECTORS
   Moderate-Performance
   a) Flat Plate:
      Flat Black
      Selective Surface
   b) High-Performance Flat Plate:
      Suppressed Convection
      Vacuum
   c) Concentrating Type
2) DEHUMIDIFICATION
3) RANKINE-CYCLE SOLAR POWER (cooling/pumping)
4) ABSORPTION A/C

Legend: ——— Probable
        - - - - - - - - - - Possible

Arthur D Little

FIGURE 2.2.2

TEMPERATURE LEVELS ASSOCIATED WITH APPLICATIONS OF SOLAR COLLECTORS

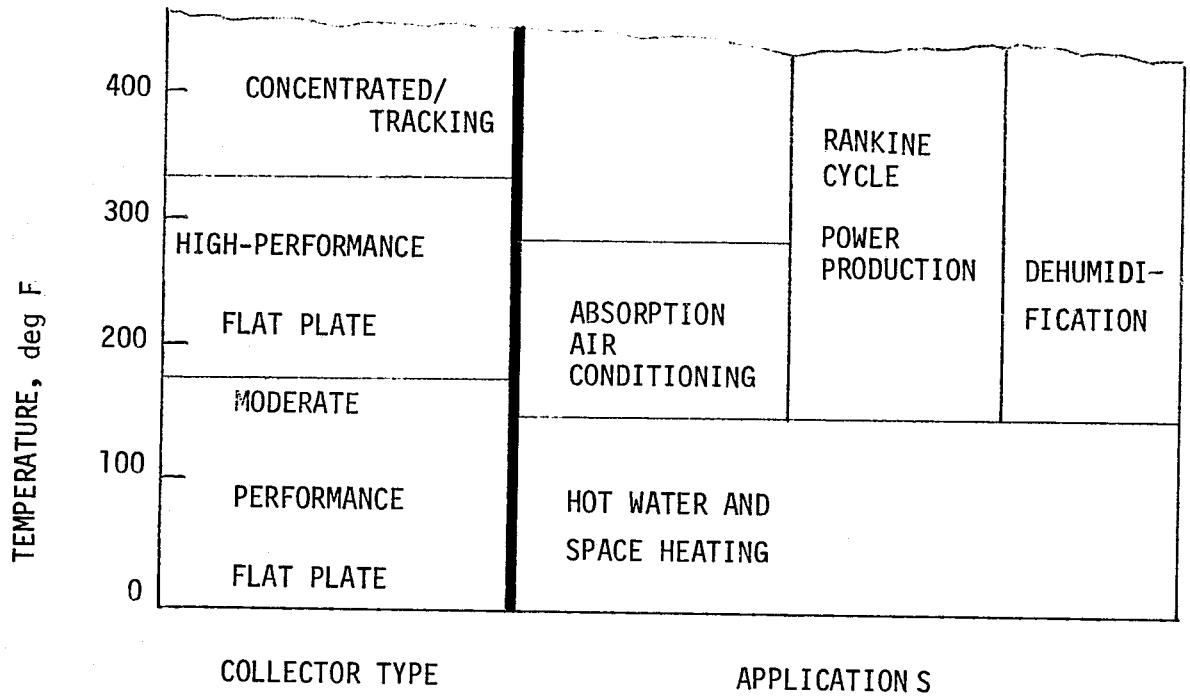


Figure 2.2.2 TEMPERATURE LEVELS ASSOCIATED WITH APPLICATIONS OF SOLAR COLLECTORS

Arthur D Little Inc

FIGURE 2.2.3

SCC SYSTEM COST/SOLAR COLLECTOR AREA

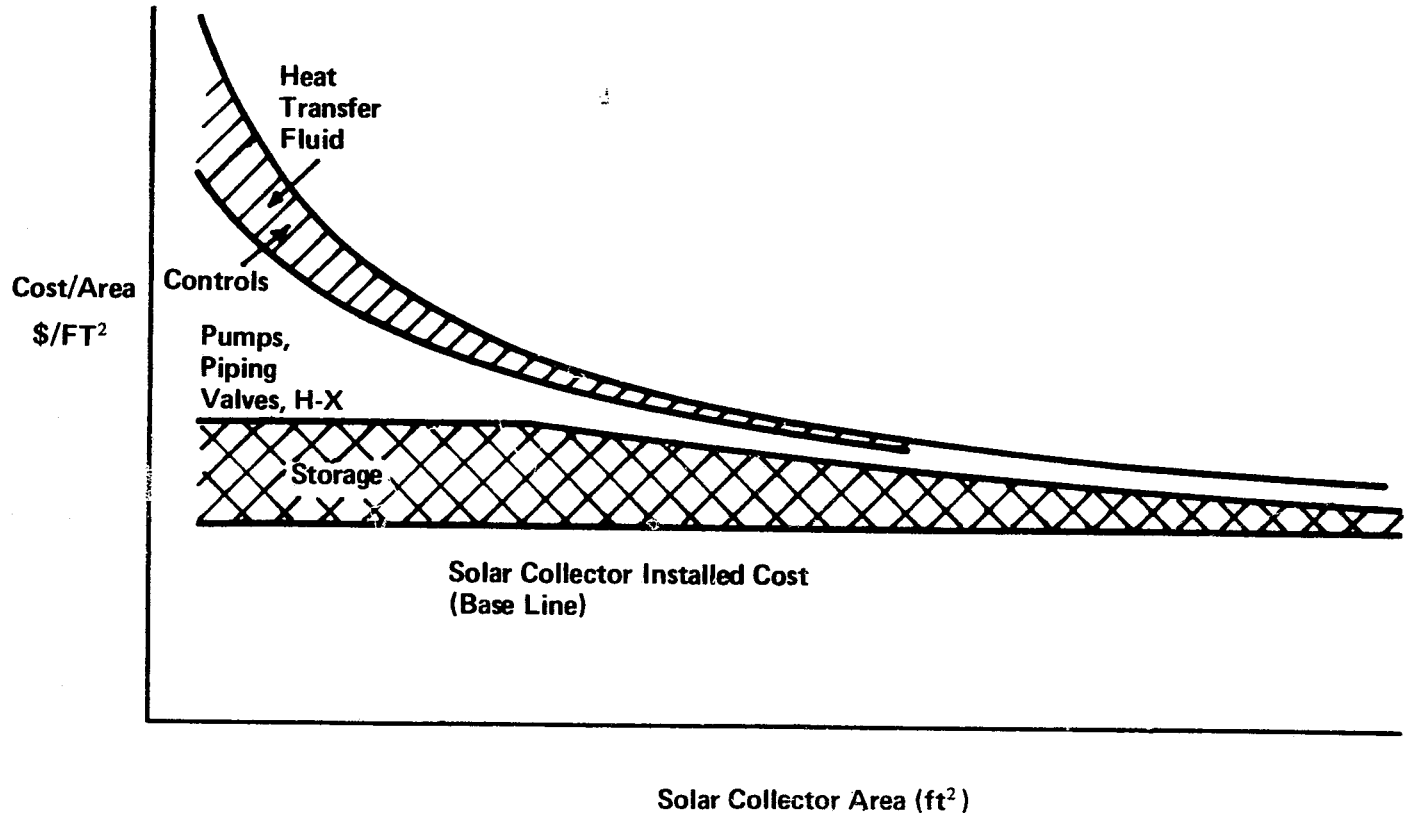


TABLE 2.2.1

SOLAR EQUIPMENT COSTS ASSUMED
FOR SYSTEM EVALUATION AND COMPARISONS

Collector Costs ($/ft^2) (mass produced and installed)

I. Baseline (current technology)--7

II. Advanced Technology--11

Incremental System Costs ($/ft^2 of collector)

	Collector Area (ft^2)			
	0-50	50-100	100-500	>500
I. Current Technology	20	15	12	10
II. Advanced Technology	25	20	17	15

NOTE: Incremental system costs are costs additional to conventional costs and include thermal storage, controls, instrumentation, etc.

Source: Arthur D. Little, Inc. estimates.

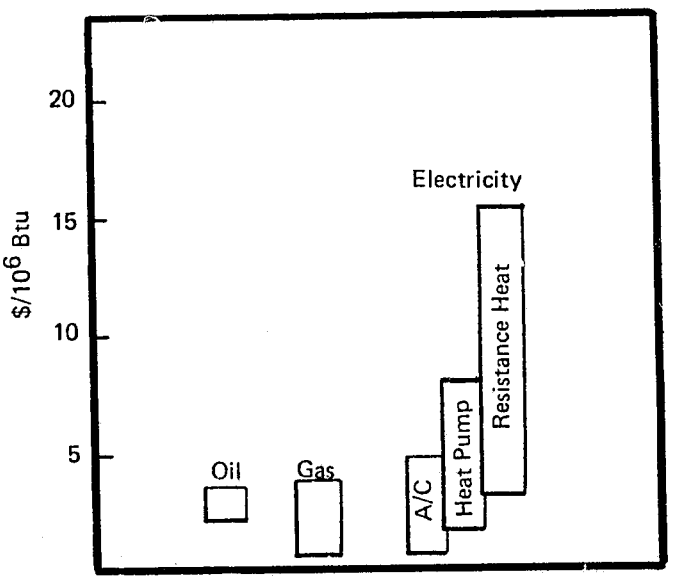


FIGURE 2.2.4 TYPICAL COSTS OF CONVENTIONAL ENERGY SOURCES

3.0 IDENTIFICATION AND PRELIMINARY EVALUATIONS OF SOLAR ENERGY CONCEPTS

As we indicated earlier, the following MIUS subsystems were examined for possible applications of solar thermal energy:

- Potable Water and Wastewater Management Subsystems
- Solid Waste Management Subsystem
- Power Generation Subsystem, and
- Heating, Ventilation and Air Conditioning Subsystems

Our search of the above subsystems for potential solar candidates focused on identifying large, direct energy uses where solar energy could be used to displace part of the load and thus effect an immediate fuel savings. Examples of these kinds of loads include: domestic hot water and space conditioning in the single-family detached residences located in the Neighborhoods, continuous water pumping machinery in the water treatment plants, auxiliary vapor-compression air conditioning in the Central HVAC subsystem, and incineration of wet solids in the waste water and solid-waste treatment plants, to name a few. Attention was also directed to examining alternative power production derivable from the sun and waste heat from the MIUS. Finally, energy savings through optimization of subsystem performance levels was examined in the case of the wastewater treatment plant.

Before we examine the identified solar concept candidates, it will be helpful to formally define several of the performance indices used in the screening procedure.

Performance Indices of Solar Energy Systems

We may characterize the solar thermal energy systems' behavior by various performance indices. The indices we will refer to in the discussion to follow are:

1) annual system efficiency,
2) percent solar,
3) solar heat cost, and
4) straight payback period, as defined below:

- Systems Efficiency (η)

Annual system efficiency is defined as the ratio of the energy collected and utilized to the annual energy incident on the solar collector:

$\bar{\eta} = Q/Q_i$

Q = annual energy collected and utilized

Q_i = annual solar energy incident on the (tilted) solar collector surface

- Percent Solar (%S)

The fraction of the load met by the solar system is characterized by the percent solar index:

$$\% S = 100\ Q/Load$$

where

Load = annual thermal energy load

- Solar Heat Cost (SHC)

Solar heat cost is defined as ratio of capital charges for the solar system to the solar energy supplied:

$$SHC = RC/Q$$

where

C = incremental capital cost of a solar thermal energy system

R = amortization rate (fraction of capital costs that must be paid each year)

- Straight Payback Period (SPP)

The straight payback period is defined as:

$$SPP = \frac{\text{Solar System incremental capital cost}}{\text{Annual operating cost savings}}$$

Neglecting minor operating cost items such as pump power-dissipation and maintenance costs, the SPP can be approximately by

$$SPP = \frac{C/A}{\bar{\eta}\ (Q_i/A)\ (V/Q)}$$

where

Q_i/A = annual insolation per unit collector area

C/A = system capital cost per collector area

V/Q = "value of collected heat," which is related to the cost per energy unit of the conventional energy displaced by solar energy, and the ratio of conventional energy input to solar heat input to accomplish the desired heating or cooling function.

3.1 Wastewater Management Subsystem

3.1.1 Subsystem Requirements

Wastewater in the Village Complex is treated using a conventional biological system designed for a 1.675 mgd capacity. A schematic of the plant is shown in Figure 3.1.1. The following processes are used in the system: sedimentation, biological nitrification/denitrificiation clarification, coagulation/flocculation, disinfection and carbon absorption with carbon regeneration. Sludge conditioning is performed by using a gravity thickener, vacuum filter and an incinerator, with ultimate ash disposal being a landfill.

The wastewater subsystem was designed using the ground-rule that the effluent quality from the treatment plant would be acceptable for discharging the effluent to the environment and also using the effluent for process water and irrigation.

The primary energy inputs to the wastewater treatment plant are in the form of electricity supplied to the various pump motors and in the chemical energy of fuel oil used to incinerate the accumulated sludge byproduct. The pump motor power requirements will be considered in greater detail in Section 3.3.2, where alternate power generation schemes shall be investigated. We are concerned in the present section with reducing the magnitude of the motor loads, and lowering or eliminating fuel consumption in the incineration of the residual sludge.

It is clear that the energy content of the fuel oil expended in the sludge incinerator is equal (excluding combustion inefficiencies) to the energy required to liberate sufficient water to allow the heating value of the remaining sludge to sustain the combustion reaction. Any reduction in sludge moisture content is thus reflected as a fuel savings.

Not so obvious is the electrical energy savings possible by controlling the influent wastewater temperature. Because of large seasonal variations in this influent temperature, sewerage treatment plant components have to be sized for conditions of less than ideal rates of digestion of the biodegradable components of the wastewater. This has

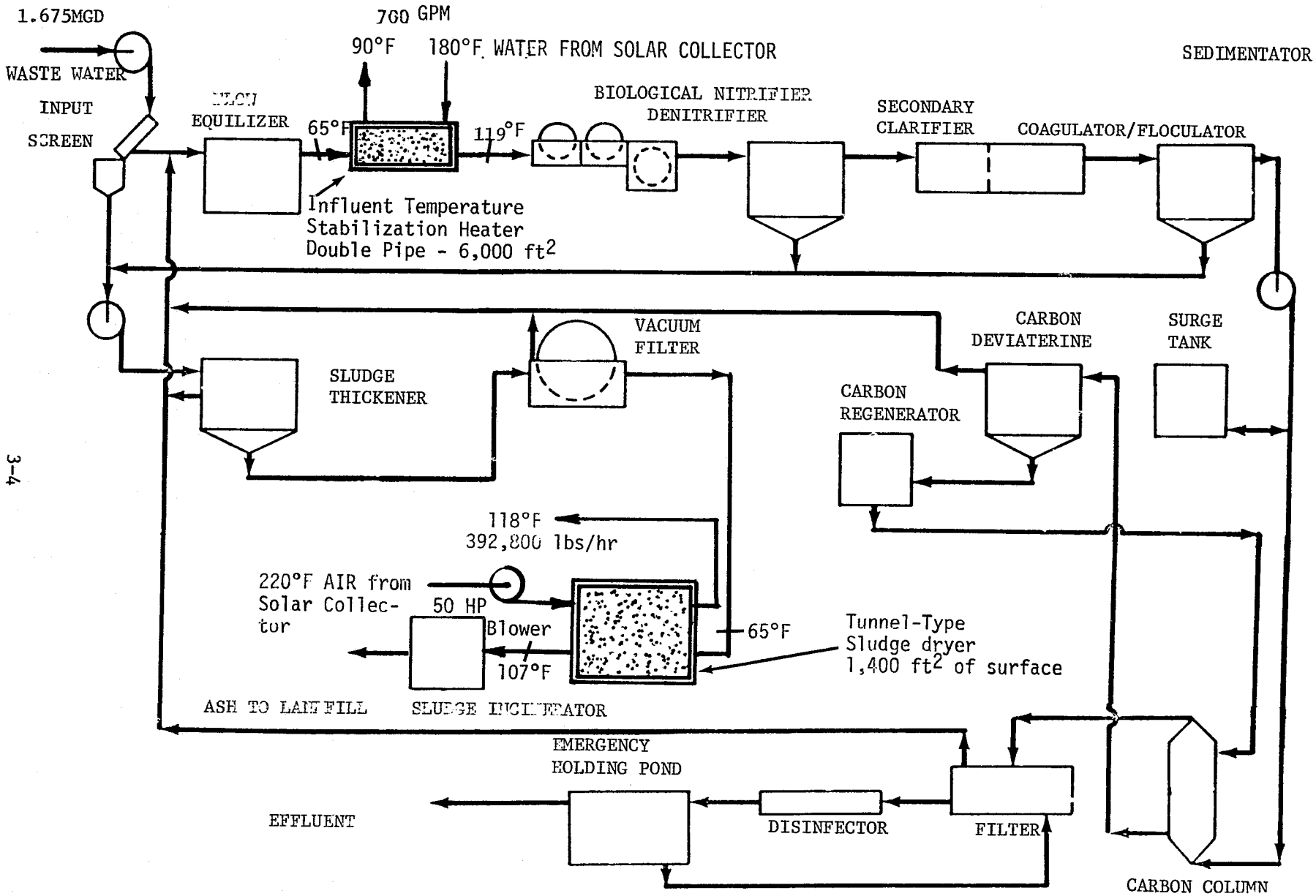


Figure 3.1.1 SCHEMATIC OF WASTEWATER TREATMENT PLANT WITH SOLAR SLUDGE DRYING OF INFLUENT TEMPERATURE STABILIZATION

the unfavorable effect of increasing pump motor power requirements. A reduction in this energy expenditure appears possible, however, through controlling the influent temperature.

3.1.2 Description of Solar Wastewater Conditioning Concepts

3.1.2.1 Sludge Drying

NASA has previously considered reducing fuel oil consumption in the MIUS Wastewater Treatment Plant by replacing the special sludge incinerator with a sludge drier. The energy required to fire the drier was presumed to be excess high grade heat from the diesel engine exhaust and solid waste incinerator. Following drying, the sludge was to be transported to the main solid waste incinerator for disposal. Fuel savings resulting from this technique were computed by NASA to amount to 992.8 GPD (23.6 bbl), or 8628 bbl/yr.

While it is true that MIUS has a net amount of unused waste heat at the end of each year, a deficiency of waste heat exists in the summer season. For this reason, an alternate source of inexpensive heat is desirable for sludge drying. Solar energy is a candidate for this application.

The solar sludge drying concept considered here embodies the usage of an array of once-through, forced-air solar collectors. An insulated duct network would combine the hot air passing from the solar collector panels and deliver this air to a direct-contact, tunnel-type sludge drier. Passage of this hot air over the effluent wet sludge will cause evaporation of enough water to enable self-sustained combustion of the remaining sludge. Figure 3.1.1 displays the sludge drier located within the wastewater treatment plant (it is to be noted that the sludge incinerator shown in this figure would be removed if the sludge drying concept were adopted). A tunnel-type drier was selected based on the knowledge that sludge dries slowly and tends to be sticky.

Air is a natural heat transfer fluid choice in the present situation since direct contact evaporation in the sludge drier is highly desirous, and freeze-up problems are eliminated in the solar collector panels. However, because of the large pressure drops associated with air-type heat exchangers, we anticipate significant auxiliary blower power requirements with this drying concept.

3.1.2.2 Wastewater Influent Temperature Stabilization

NASA has also investigated the energy savings resulting from a reduction in the size of the wastewater treatment plant. This could, presumably, be accomplished by thermally enhancing the influent sewerage using a heat exchanger upstream of the plant (shown schematically in Figure 3.1.1). The heat exchanger will utilize excess high-and-low grade waste heat. Through this method, incoming wastewater at 65°F was predicted to be raised to between 109 and 124°F. In this early work no quantitative estimate was made of the reduction in power requirements

that could result from improved operating conditions.

For reasons similar to that stated for sludge drying, solar energy should be considered as an alternate candidate source of heat for wastewater influent temperature stabilization. In the solar concept, we visualize an array of water-cooled solar collector panels supplying hot liquid to a double-pipe heat exchanger located at the intake pipe of the treatment plant. The rationale for this choice of heat exchange is based on experience which indicates that sewerage tends to have poor heat transfer characteristics, and a double-pipe heat exchanger would be more readily maintainable.

3.1.3 Performance Characteristics of Solar Wastewater Conditioning Concepts

The analyses of both the solar wastewater conditioning concepts listed above were conducted considering advanced technology collector systems with annual operating characteristics taken from our computer simulation data base. Knowing the heat loads, it was thus possible to estimate the collector size requirements using as reasonable guides the following percentages: 25% annual collector efficiency, and 60% of the load will be met by the solar collection subsystem. The solar insolation used in the analyses corresponded to the conditions of Washington, D. C., which is 0.56×10^6 BTU/ft^2/yr.

3.1.3.1 Sludge Drying

The heat load on the sludge drier was not specified in the "MIUS Community Conceptual Design Study".[4] We are therefore required to estimate this load based on several elements: A) the total stipulated flow rate of wastewater in the Village Complex, B) the proportion of organic solids in the total flow, and C) thermal conditions based on our experience in the treatment of sewerage. The organic solid content of the sewerage influent was also not provided in the Village Complex study, but was available in the 500-unit apartment complex study ("Preliminary Design Study of a Baseline MIUS System").[5] To get a first order heat load estimate, we therefore assumed that the solid-to-total flow rate ratio is proportional in these two situations. As a result of this assumption, the dry solid content of the sewerage influent was computed to be 17,080 lbs/day.

Using the 17,080 lbs/day of dry solids, and the 1.675 mgd of total flow, the annual thermal load on the solar collection system will be 22.6×10^9 BTU. Figure 3.1.1 summarizes the inlet and exit conditions, and the total hot air flow rate for the operation of the sludge drier. Also given is the 50 HP power requirement of the hot air and solar-collector blower motors; Table 3.1.1 provides a summary of other analysis assumptions and the performance and economic characteristics of the solar drying concept. The annual thermal and electrical energy requirements are based on 6 hrs/day operation of the drier, 365 days/yr.

TABLE 3.1.1

APPLICATION SLUDGE DRYING

ANNUAL LOAD 22.6×10^9 BTU, Thermal(1)

CONCEPT	SOLAR COLLECTOR TEMP LEVEL & DUTY	SOLAR COLLECTOR TYPE	SOLAR COLLECTOR AREAS(2)	IMPACT ON MIUS	TECHNOLOGY STATUS	ECONOMIC CONSIDERATIONS(4)
Replacement of Special Sludge Incinerator by a Solar-Heated Sludge Dryer. Dried Sludge to be burned in Solid Waste Management Incinerator. Hot Air Generated in Solar Panels used to Directly Dry Sludge.	220°F Over 6 Hrs per day	Once-through Forced Air Advanced Technology	100,000 ft^2 collector 4.6 Acres of Land	Sludge Heating Value Raised, Resulting in Decreased Incineration Fossil Fuel Consumption 4,300 BBL/YR(5) Sludge Incinerator Eliminated Increased Auxiliary Electrical Load -- 82×10^3 KW - HRS(3)	Tunnel-type Sludge dryer Commercially Available Collectors Under Development	Incremental Capital Cost of Solar Dried Sludge = \$8.0/MMBTU for Solar Collection Subsystem + \$1.5/MMBTU for Sludge Dryer Subsystem \$9.5/MMBTU of Useful Solar Energy Collected

(1) Conditions: A) 17,089 lb/day of dry solids; B) Filter Cake = 80% H_2O; C) Dried Sludge = 40% H_2O; D) Inlet Drying air humidity equiv. to 80% R.H. at 90°F; E) Inlet Temp. = 65°F, outlet temp. = 107°F; F) 6 HRS/Day Operation, 356 Days/YR.

(2) Conditions: A) 25% annual collection efficiency; B) 60% of load met by solar subsystem; C) Annual Incident Energy = 0.556×10^6 BTU/ft^2; D) Land area = 2 x collector area.

(3) Condition: Collector blower and dryer blower total motor ≅ 50 HP.

(4) Conditions: A) Cost of dryer, shredder, instrumentation, controls, ducts, insulation, motors, etc. ≅ \$200,000; B) Cost of Solar subsystem = \$11/ft^2

(5) Conditions: A) Heating value of fuel oil = 150,000 BTU/GAL; B) Combustion efficiency = 50%

No provisions have been made in this study for odor control from the drier. Experience would indicate that odors would be expected unless the filter cake has been highly limed and, even then, it is doubtful that the exit air would not require some treatment. Typically odor destruction requires either thermal oxidation at temperatures from 600°F (catalytic) to 1200°F (direct oxidation) or removal by oxidents in liquid scrubbing systems. We have attempted to minimize the land area impact on the Village Center by utilizing performance characteristics of advanced technology solar collector panels. Even with this consideration, the solar array needed to meet 60% of the thermal load would use approximately one-half the unstructured land in the Village Center. The increase in auxiliary electrical energy amounts to approximately 0.07% of the annual Village Complex demand of about 120×10^6 Kw-hrs.

The potential economics of the solar sludge drying concept is dependent, as a minimum, on the following cost elements:

Cost Increases:

- Sludge Drier (∿$200,000)
- Solar Collectors and Ancillary Equipment (∿$1,100,000)
- Larger, more complex solid waste incinerator (neglected in preliminary evaluation)
- Conveyor system from sludge drier to solid waste incinerator (neglected in preliminary evaluation)
- Auxiliary electric motor energy ($\sim 82{,}000 \frac{\text{KW-HRS}}{\text{YR}}$, $\frac{2460}{\text{YR}}$ @ $.03/Kw Hr)
- Land usage (neglected in preliminary evaluation)

Cost Savings:

- Fuel use reduction (4,300 bbl/yr or approximately 2% of MIUS annual fuel consumption)
- Elimination of sludge incinerator and separate refuge handling (neglected in preliminary evaluation)

If sufficient excess waste heat from MIUS is available year round to provide the drying function, clearly the solar concept becomes uncompetitive.

3.1.3.2 Wastewater Influent Temperature Stabilization

Figure 3.1.1 displays the end state flow conditions of the double-pipe heat exchanger considered for stabilizing the wastewater influent temperature. The stabilized temperature chosen in the analysis is 119°F. This is the mean of the four seasonally stabilized temperatures computed by NASA and provided in Table VI-6, P 457 of Ref. 4.

additional region. As a result, the heat addition process in the ideal Rankine engine becomes non-isothermal and the average temperature of heat addition is lower than the upper temperature in the corresponding Carnot cycle. This causes the ideal Rankine-cycle efficiency to fall below the corresponding Carnot efficiency.

In real Rankine-cycle engines, additional degradations in efficiency are experienced because of additional irreversibilities in pumps, expanders, and heat exchangers. However, modern design practices have raised the thermal conversion efficiency of Rankine-cycle engines to within approximately 65% of the Carnot efficiency for the presently available temperature levels. Advanced technology developments may raise this percentage to 68%, or higher.

A number of studies have investigated the optimum choice of working fluids for use in a solar-activated Rankine-cycle engine. The concensus of these investigations is that water is an inappropriate working fluid in comparison to performance levels attainable from organic fluids, including several common refrigerants. Because many of these organic fluids promote superheating of the expanding vapor during the work extraction process (i.e., they are "drying fluids"), a regenerative heat exchanger is needed to improve cycle efficiency. Figure 3.3.2 displays the regenerated Rankine-cycle for an organic working fluid. Also included in the figure is an equipment schematic needed to accomplish the cycle.

3.3.2.1 Solar-Heated Rankine-Cycle Engine Water Pumping Power

There are a number of possible applications within the Village Complex MIUS for solar generated power; Figure 3.3.3 displays several candidates. The economic feasibility of the solar power generation concept is, however, highly dependent on the ability to amortize the high initial capital investment in equipment. For this reason, steady base load applications are preferred to intermittent power uses. Thus, applications dedicated to loads such as the incineration blower, etc. are unattractive.

A likely steady base-load application of solar power in the Village Complex is the main wastewater pumps in the sewerage and potable water treatment plants. Furthermore, there is great incentive here to directly harness the heat engine output to these pumps (via gear boxes, couplings, clutches, shafts, etc.) to remove the inefficiencies associated with generators, transmission lines, and drive motors. A key requirement of this scheme is, of course, that the heat engine must be located in close proximity to the pumps. Another obvious requirement is the need for backup motors for these periods when solar energy is unavailable. Figure 3.3.4 schematically portrays the concept.

As in the sludge drier study, the total influent flow rate was taken to be 1.675 mgd; however, the operation of the influent heat exchanger is continuous throughout the year.

Table 3.1.2 summarizes the performance and economic features of the wastewater temperature stabilizing heat exchanger, along with a listing of additional analysis conditions and assumptions. Again, the emphasis was to reduce the operating costs of the wastewater treatment plant, but with a minimum land area impact on the Village Center. Advanced technology collectors were therefore considered in the study. As can be seen, the solar collector panel array required to meet 60% of the thermal load requires all of the unstructured and park land in the Village Center plus 20 acres of unavailable developed land. Apart from any energy savings, this result would seem to preclude further consideration of the concept, given present ideas on land and space utilization in a community. It is a stark prospect to visualize solar collector panels covering roofs, parking lots, and all other open space in a community.

Unquestionably as a formal exercise, we list the cost elements of the Wastewater Temperature Stabilization concept which bear on its economic feasibility:

Cost Increases:

- Influent heat exchanger (∿$90,000)
- Solar collectors and ancillary equipment ($13,200,000)
- Auxiliary electric motor energy (98,000 Kw-Hr/yr, $3,000/yr @ $.03/Kw-Hr)
- Heat exchanger maintenance
- Land usage (neglected in preliminary evaluation)

Cost Savings:

- Reduced pump motor loads through plant size reduction.

3.2 Solid Waste Management Subsystem

3.2.1 Subsystem Requirements

Solid wastes generated in a Village Complex are to be burned in four 3000 lbs/hr incinerators, with ultimate disposal of the residual ashes being in a remote landfill. In this manner, 89,749 lbs/day of solid wastes will be partially converted to heat. Some of this heat (180×10^9 BTU/yr) will be recovered at 250°F using low-pressure steam heat exchange units. This steam is tied into the heat recovery system on the exhaust of each prime mover. Wherever possible, the heat recovery equipment used in the incinerators was designed to be compatible with the HVAC subsystem. Burning schedules of the solid wastes shall conform to the

TABLE 3.1.2

APPLICATION WASTE WATER INFLUENT TEMPERATURE STABILIZATION

ANNUAL LOAD 276×10^9 BTU(1)

CONCEPT	SOLAR COLLECTOR TEMP LEVEL & DUTY	SOLAR COLLECTOR TYPE	SOLAR COLLECTOR AREAS(2)	IMPACT ON MIUS	TECHNOLOGY STATUS	ECONOMIC CONSIDERATIONS(4)
Water treatment Temperature stabilization through Employment of influent heat exchanger	180°F Continuous	Water Coolant Advanced Technology	1.2×10^6 ft^2 Collector 55 Acres of Land	Increased Auxiliary Electrical -- 98×10^3 KW-HRS(3) Solar Collectors Would Require all Undeveloped Land (Park, Recreational, and Unstructured) in Village Center (35 Acres) plus 20 Additional Acres. Reduction in size of Waste Treatment plant because of Increase Efficiency	Double-pipe Heat Exchanger Available. Collectors under Development	Incremental Capital Cost of Solar Temp. stabilized water = \$8.0/MMBTU for Solar Collection Subsystem + 5¢/MMBTU for Heat Exchange Equipment = \$8.1/MMBTU of Useful Solar Energy Collected

(1) Conditions: A) 1.675×10^6 GAL/DAY, 365 Days/YR; B) Inlet temperature = 65°F; C) Outlet Temperature = Annual Mean Stabilized Temperature = 119°F; D) Waste Water Specific Heat = 1 BTU/lb-°F

(2) Conditions: A) 25% annual collection efficiency; B) 60% of load met by solar system; C) Annual Solar incident energy = 0.556×10^6 BTU/ft^2; D) land area = 2x collector area

(3) Conditions: A) Pump Motor loads = 15 HP; B) 24 HR/DAY, 365 Days/YR operation

(4) Conditions: A) Cost of heat exchange equipment = \$90,000; B) Cost of Solar System = \$11/ft^2; C) Cost of Land = \$0/ft2; D) Amortization Rate = 10%/YR

requirements of the HVAC subsystem. The utilization of supplemental fuel in the incineration process was minimized. Stack emissions have been designed to comply with EPA guidelines. (Figure 1.3.1 schematically depicts the relationship of the solid waste incinerator to the MIUS, while Figure 1.3.2 gives the annual energy utilization.)

Conventional incineration of average solid wastes is an exothermic process and thus requires auxiliary fuel only during initial startup. The heating value of the wastes is, however, dependent on the moisture content decreases. The loss in potential trash heating value is easily identified as the energy required to liberate absorbed and inherent water in the trash.

3.2.2 Description of Solar Solid Waste Conditioning Concept: Solid Waste Drying

From the above discussion we can visualize an increase in the production of recovered incinerator heat created through drying the influent trash prior to incineration. This extra heat can find utility in augmenting the short supply of waste heat required to "fire" the absorption air conditioning equipment, thus displacing vapor-compression auxiliary air conditioning and reducing the electrical load on the MIUS.

The solar solid waste drying concept shown schematically in Figure 3.2.1 is directly analogous to the sludge drying concept considered in the previous section. Hot air generated in once-through, forced-air solar collector panels would be ducted to a direct-contact drier on the inlet of the incinerator. Passage of this hot air over the trash influent causes evaporation of water contained within the trash.

Air is again a prime heat transfer medium candidate in this drying application since direct-contact evaporation is a highly desirous process. However, for trash drying to be effective - whatever the fluid medium - the solid wastes must be exposed and be in small sizes. These conditions imply the need of a trash shredder to puncture and destroy plastic bagged trash. Tearing the solid wastes into smaller units increases the exposed surface areas and reduces the drier size.

3.2.3 Performance Characteristics of Solar Solid Waste Drying

The performance analysis of the solar solid waste drier was guided by the same basic design philosophy used in the wastewater conditioning analyses: the solar collector panels were assumed to be advanced technology equipment which produce a 25% annual collector efficiency, while 60% of the load is met by the solar collection system. Washington, D. C. was considered the location of the system, where the annual solar insolation is 0.56×10^6 BTU/ft^2/Yr.

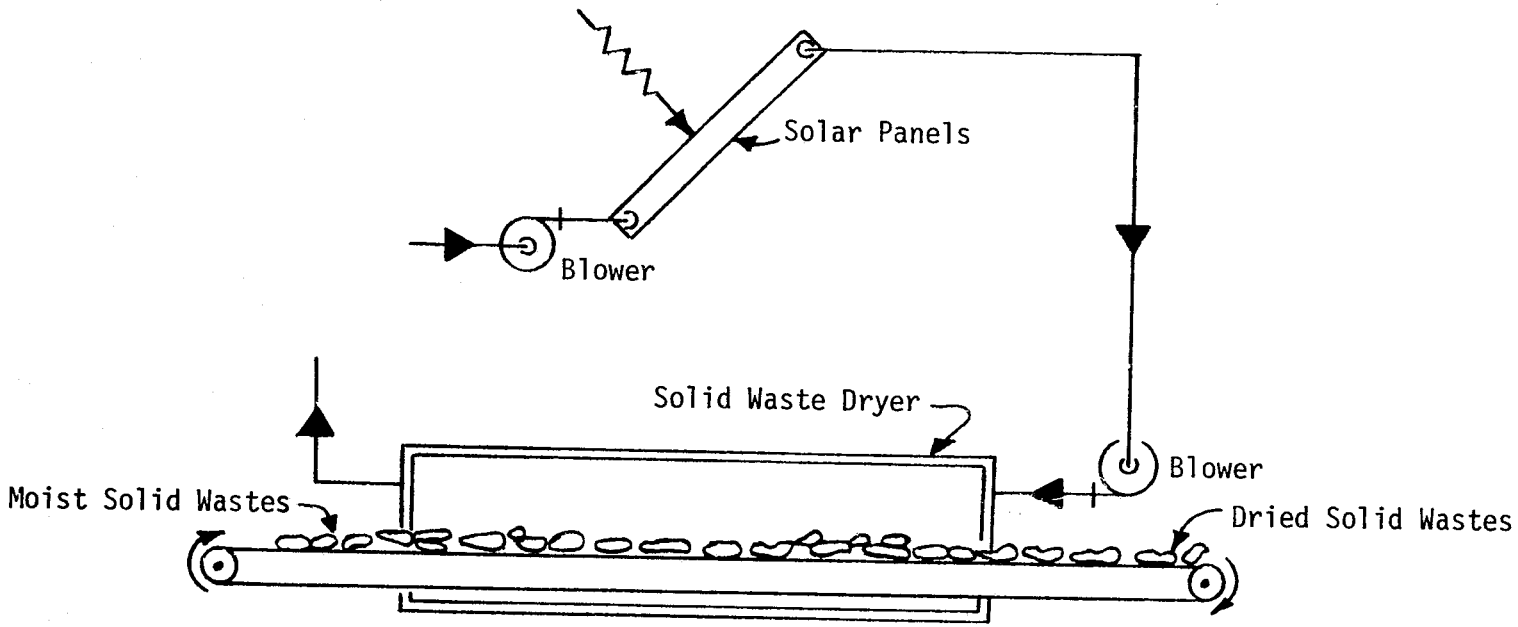


FIGURE 3.2.1

SOLAR SOLID WASTE DRYING CONCEPT

From our experience in the design of solid waste disposal facilities, we based the thermal load of the drier on a 25% moisture content at the drier inlet and a 10% moisture content at the discharge of the drier. The water thus removed constitutes about 17% of the daily total solid-plus-liquid flow rate of 89,749 lbs., or 15,000 lbs/day of water removed via evaporation. Considering 1000 BTU/lb as an average heat of vaporization of water, the annual load on the drier is about 5.5×10^9BTU. This energy, which is also the increase in the heating value of the dried trash, is about 3% of the heat output of the undried trash incinerator. (see Figure 1.3.2). Of course, not all of the 5.5×10^9BTU is recoverable because of heat transfer inefficiencies and stack gas losses.

Table 3.2.1 summarizes the performance and economic characteristics of the solar solid waste drying concept; also included are the main assumptions governing the predictions. As may be seen, one acre of land would be required in the Village Center for advanced technology collector system which meets 60% of the thermal load. Because of the large pressure losses associated with air collectors and air driers, approximately 150×10^3KW-HRS of auxiliary electrical energy would be needed to drive the blower motors. This energy is about 0.13% of the MIUS electrical load of 120×10^6 KW-HRS.

The potential economics of solar solid waste drying is dependent, as a minimum, on the following elements:

Cost Increases:

- Drier
- Pretreater (for course shredding)

} (∿$250,000)

- Solar collection and distribution equipment (∿$264,000)
- Electrical power to operate blowers and motors ($\$150 \times 10^3 \frac{\text{KW-hr}}{\text{yr}}$, $4500/yr @ 3¢/KW-Hr)
- Additional supervisory and maintenance personnel
- Land usage

} Neglected in preliminary evaluation

TABLE 3.2.1

APPLICATION: SOLAR SOLID WASTE DRYING

ANNUAL LOAD: 5.5 x 10^9 BTU Thermal (1)

CONCEPT	SOLAR COLLECTOR: TEMP LEVEL & DUTY	SOLAR COLLECTOR: TYPE	SOLAR COLLECTOR: AREAS(2)	IMPACT ON MIUS	TECHNICAL STATUS	ECONOMIC CONSIDERATIONS(4)
Lower moisture content of influent trash using hot air generated in solar panels	220°F as required by HVAC system	Once thru forced air Advanced Technology	24,000 ft^2 Collector One Acre of land	Increased solid-waste heating value raises annual surplus of waste heat Increased auxiliary Electrical load -- 150 x 10^3 KW-HR/YR (3)	Drying Equipment Available - Collectors under development No operating experience with burning shredded trash	Incremental Capital Cost of Solar dried trash = $8.0/MMBTU for Solar Collection subsystem + $7.6/MMBTU for Dryer Subsystem = $15.6/MMBTU or Useful Solar Energy Collected

(1) Conditions: A) 89,749 lb/day of solid wastes; B) inlet moisture content = 25%; C) outlet moisture content = 10%; D) Heat of vaporization of water = 1,000 BTU/lb

(2) Conditions: A) 25% annual collection efficiency; B) 60% of load met by solar system; C) Annual Solar Incident Energy = 0.556 x 10^6 BTU/ft^2

(3) Conditions: A) Collector blower, fryer blower, and shredder total motor load $\simeq$ 50 HP; B) 11 HR/Day, 365 Days/YR operation

(4) Conditions: A) Cost of dryer, shredder, instrumentation, controls, ducts, insulation, motors, etc. $\simeq$ $250,000; B) cost of solar subsystem = $11/$ft^2$; C) Cost of land = $0/$ft^2$; D) Amortization Rate of capital costs = 10%/YR

3.3 Power Generation Subsystem

3.3.1 Subsystem Requirements

The power generation subsystem in the Village Complex (shown schematically in Figure 1.3.1 consists of eight (8) 4,415 kW diesel generators, for a total peak capacity of 35.32 MW. These generators were designed to meet all the electrical service requirements for the Village Center and three (3) adjacent Neighborhoods. As shown in Figure 1.3.2, the annual load on the generator subsystem totals almost 120,000 MW-hrs. Figure 3.3.1 provides information on the hourly system power profile for a summer day. It can be seen from this figure that the peak demand is about 31.5 MW, occurring at 7:30 p.m., whereas the noontime demand is approximately 25 MW.

Useful heat energy is also provided to the Village Complex from the power generation subsystem. Low-grade thermal energy is taken from the intercooler, lube oil cooling system, and water cooling jacket; while high-grade heat is generated by using low-pressure steam heat recovery units on the exhaust of each prime mover. The steam header from this recovery unit is also tied into the heat recovery system of the incinerators.

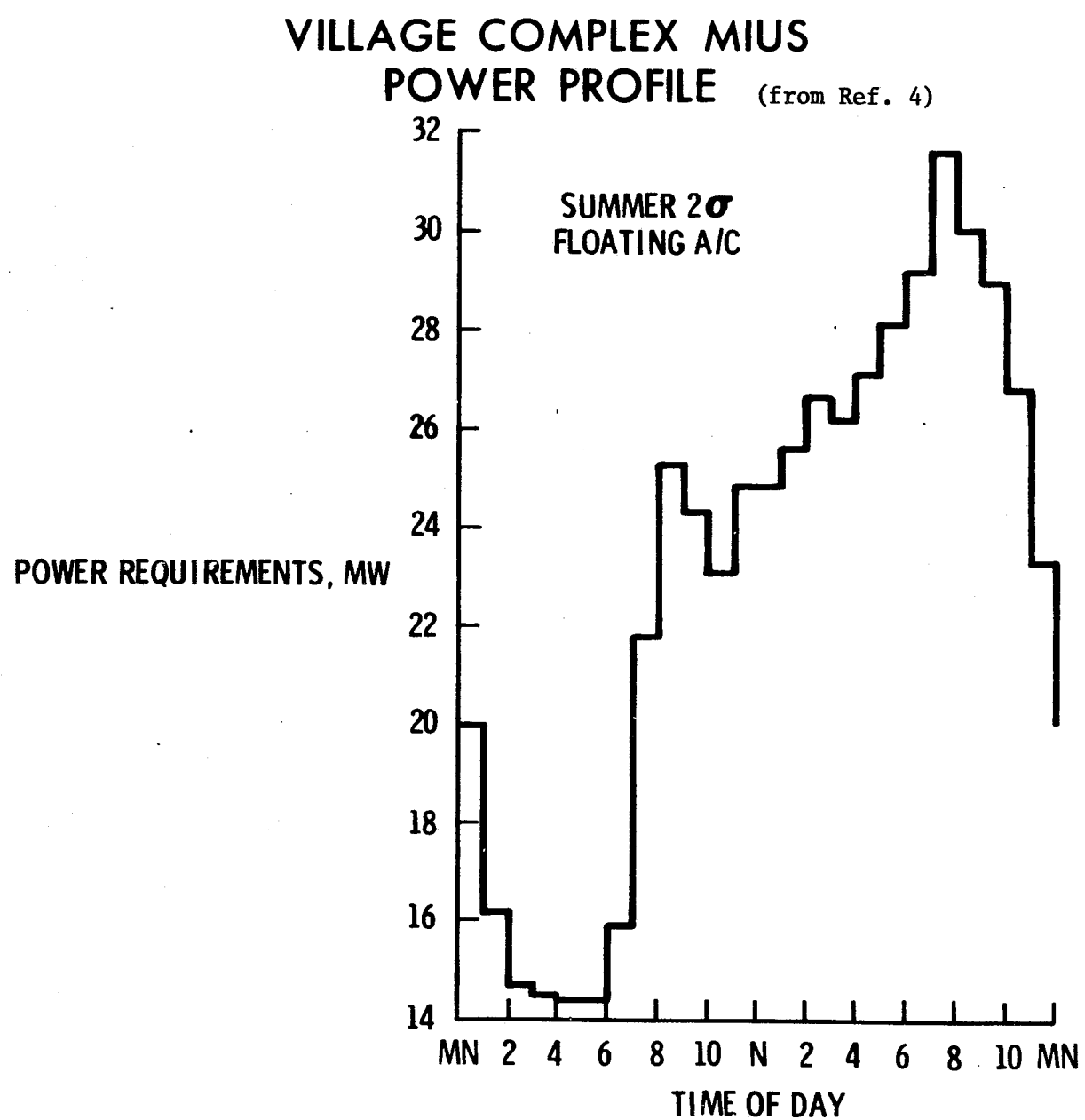
3.3.2 Description of Solar Power Generation Concepts

The minimization of diesel fuel consumption in the Village Complex has been a continuing objective of NASA in developing the MIUS concept. With the recent rapid escalation in fuel prices, and the predictions of fuel shortages in the near future, this objective has taken on increasing importance. Because of these events, alternative and possibly renewable, energy sources have been given greater interest than heretofore.

This section is concerned with establishing preliminary technical and economic characteristics of solar energy conversion systems for utilization within the Village Complex. The solar conversion systems to be considered are of the indirect conversion, thermal collection variety rather than direct photvoltaic systems. We feel this selection is compatible with NASA's time scale objective of dealing with technology capable of being developed and operational within a time frame of five years.

The solar-activated power generation subsystems under consideration can be visualized as being composed of two main components: the solar energy collectors, and the energy conversion machinery. The thermal input to the subsystem comes from the sun and is used to heat a fluid which is transported to a heat engine via a pipe network. At the heat engine, an interaction occurs with this hot fluid which causes work to be done on the environment. For this process to be successful, however, a portion of the supply heat must be rejected to a region cooler than the heat supply medium. The usual heat disposal media include the atmosphere, rivers, lakes and oceans.

FIGURE 3.3.1


VILLAGE COMPLEX MIUS
POWER PROFILE (from Ref. 4)
SUMMER 2σ
FLOATING A/C
POWER REQUIREMENTS, MW
32
30
28
26
24
22
20
18
16
14
MN 2 4 6 8 10 N 2 4 6 8 10 MN
TIME OF DAY

The solar collector devices envisaged in the solar power generation concept include the varieties previously discussed, such as flat plate, glass-enclosed, selective surface absorbers. Various configurations of components within the heat engine are possible also. However, we are concerned here with that class of heat engines designated as Rankine-cycle engines. This class of heat-energy converters is best suited for the temperature ranges expected within near-term solar collectors.

It is not our purpose here to expound at great depth on the nature, operation and selection of Rankine-cycle engines; many excellent thermodynamic text books and reports are available for that purpose. Rather, our purpose here is to point out the essential features of the engine which will allow a preliminary evaluation of its performance and feasibility in converting solar heat to work.

The Rankine-cycle engine derives its name from the closed cyclic sequence of thermodynamic processes experienced by a circulating "working fluid"; that is the Rankine cycle. In its simplest form, the Rankine-cycle engine consists of a boiler, condenser, expander, and feed pump. Heat addition in the engine occurs at the boiler, which provides saturated or superheated vapor to the expander by transferring heat from the solar-heated fluid to the Rankine-cycle working fluid. Power is extracted in the expander (either rotary, turbine, or reciprocating) after which the fluid passes on to the condenser, which supplies saturated liquid to the feed pump. The feed pump raises the pressure and resupplies fluid to the boiler, thereby completing the cycle. Heat is rejected from the working fluid in the condenser to an exterior cooling fluid. This latter fluid could be ambient air, or water from a cooling tower. The expander shaft work may be transmitted through a speed reducing gearbox and used as shaft power to drive compressors or pumps, or to drive a generator to produce electrical power.

The Rankine-cycle is a practical alternative to the Carnot thermodynamic cycle. The Carnot cycle represents the ultimate in conversion efficiency, but is unattainable because of the nonidealities in real processes. A Carnot cycle is composed of an alternating closed sequence of repeating reversible adiabatic and reversible isothermal processes. Heat is added and rejected in the cycle only during the isothermal temperature processes, which are distinct. Thermal energy conversion efficiency improvements in the Carnot cycle are solely dependent on raising the temperature of heat addition and lowering the temperature of heat rejection, with the latter process having the greater influence per unit temperature change. Although Carnot thermal conversion efficiencies are unattainable in practice, the concept still serves as a useful bench mark against which the performance of real engines may be compared.

The ideal Rankine cycle differs from the Carnot cycle in that the former efficiency is dependent on the nature of the working fluid as well as the upper and lower temperature regions of the cycle. This dependence is produced, in part, by the avoidance of pumping two-phase mixt mixtures of the working fluid from the heat-rejection temperature region to

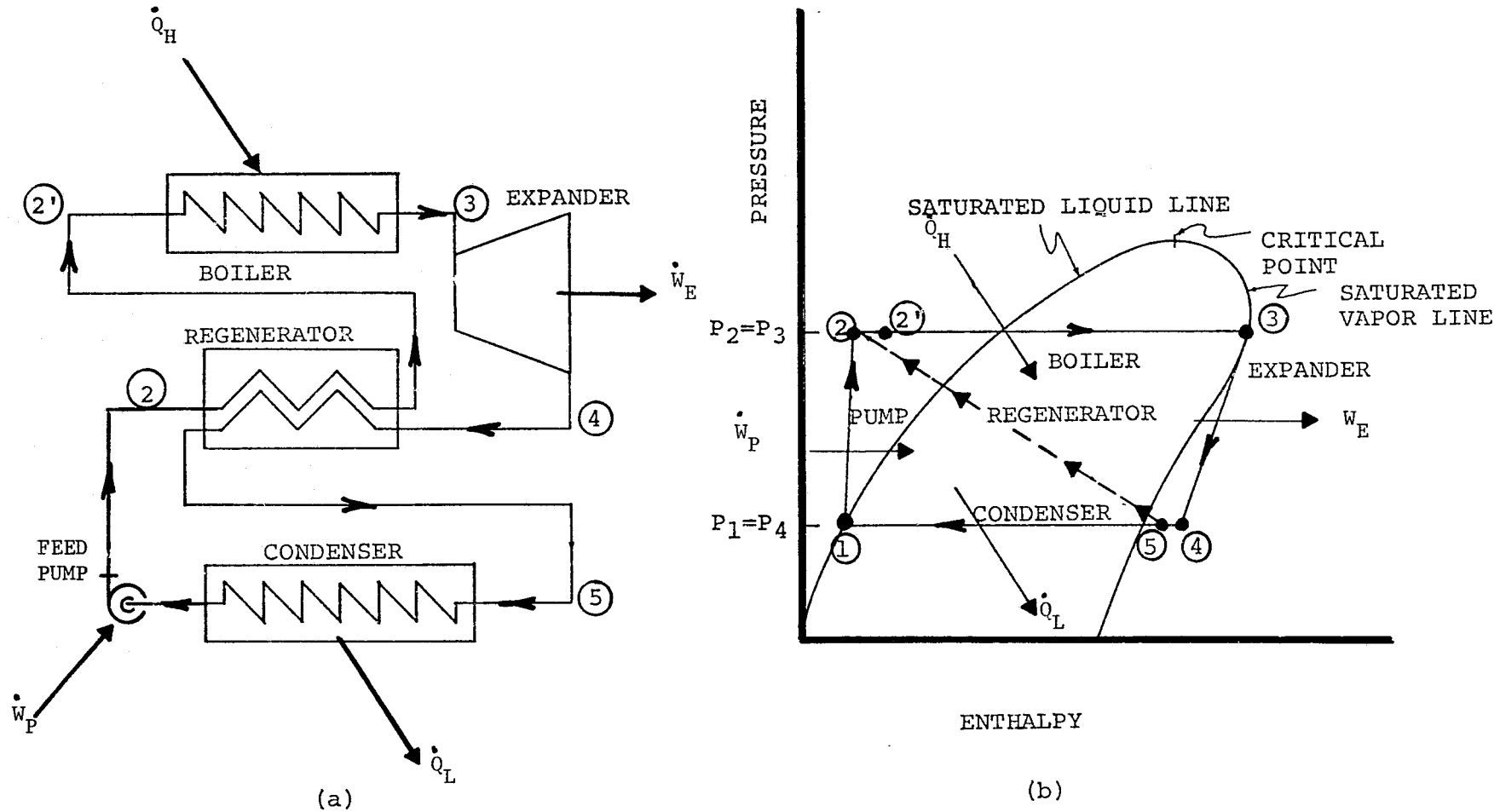
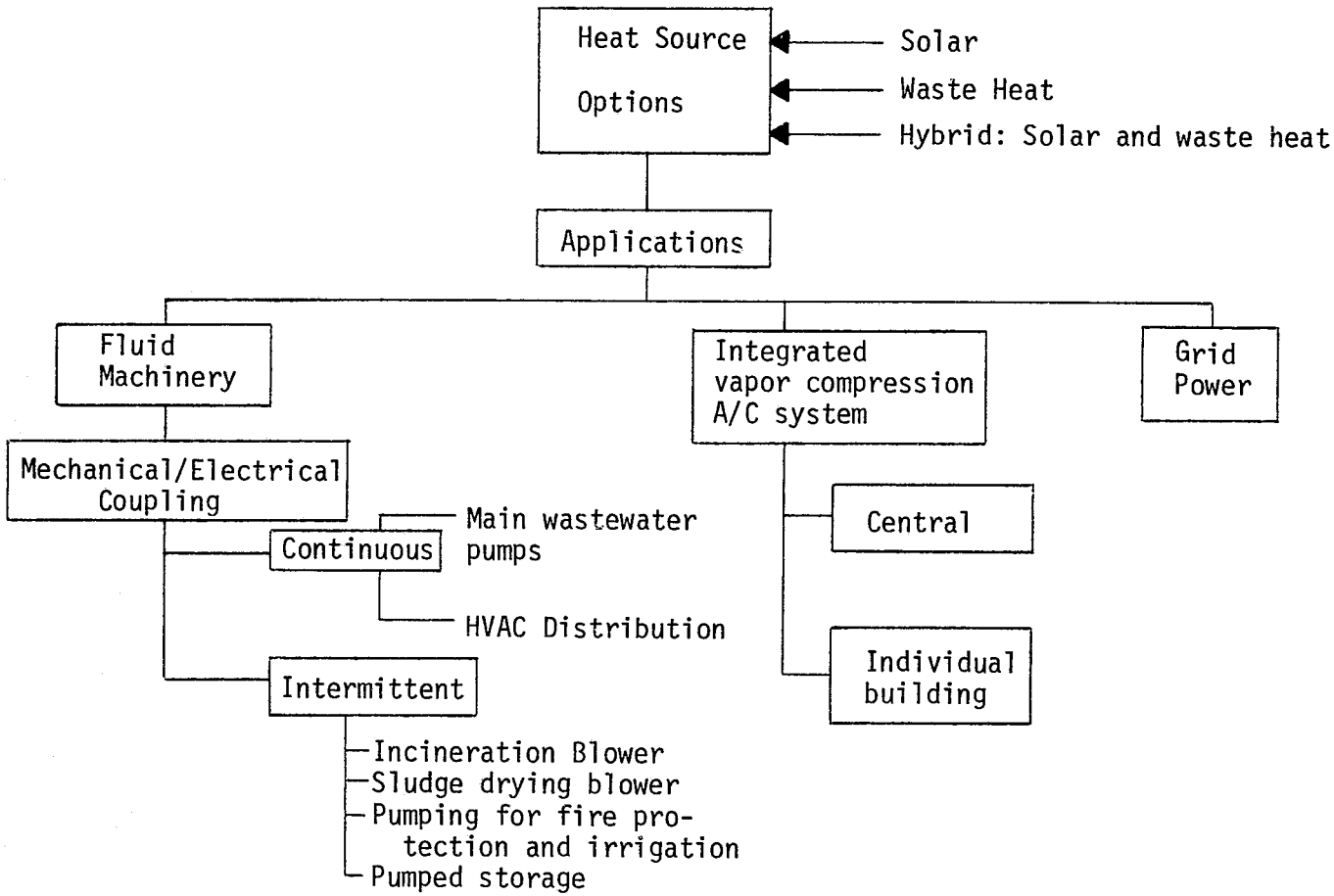


Figure 3.3.2 System Schematic and Pressure-Enthalpy Diagram for Organic Working-Fluid Rankine Cycle with Regeneration

Figure 3.3.3
APPLICATIONS OF RANKINE CYCLE ENGINES IN MIUS



Arthur D Little Inc

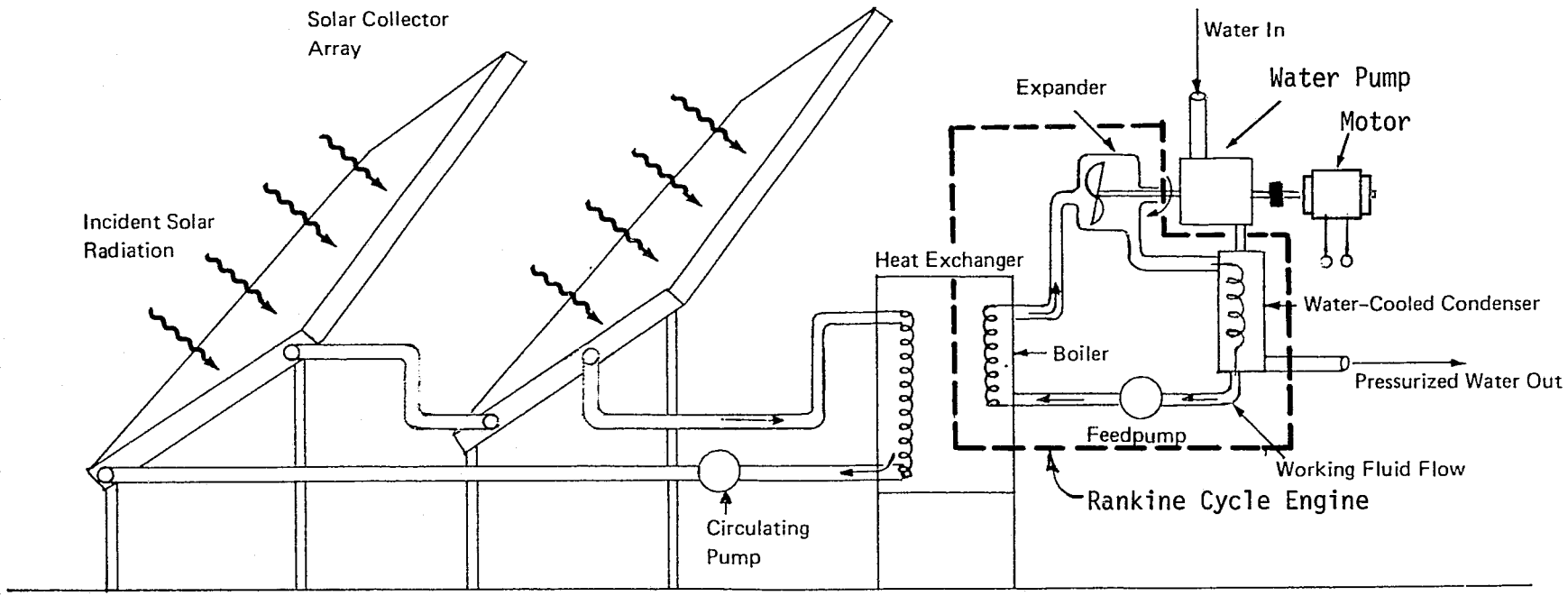


FIGURE 3.3.4

SCHEMATIC OF SOLAR-POWERED WATER-PUMPING SYSTEM -

(RANKINE-CYCLE ENGINE SHOWN MECHANICALLY COUPLED TO PUMP)

3.3.2.2 Solar-Heated Rankine-Cycle Engine Power Generation

Another initially attractive application of solar-generated power is the production of as much grid power as possible, consistent with technological constraints of the equipment and land area limitations. This concept has the advantages of always having uses for the power, and individual backup motors and controls are not required such as in the water pumping concept. The prime movers would still be sized for the peak MIUS load since there will be periods of no solar input and the solar Rankine-cycle engine will require switching, instrumentation and controls for utility interfacing.

3.3.2.3 Combined Solar and Waste-Heat Bottoming Rankine-Cycle Engine Power Generation

It may be seen in Figure 1.2.5 that an annual surplus of waste heat exists within the Village Complex MIUS. In the past, this heat would have gone unused because of unattractive energy conversion economics. Additional prime mover capacity and higher fuel consumption rates would have been the lower cost alternative. Present fuel costs and the prospect of fuel shortages have, however, altered this assessment, so that, today, all sources of low-cost available energy are being explored.

There is no technological reason why a waste-heat bottoming cycle engine cannot be placed between the reject heat of the prime movers and incinerators and the ambient. Indeed, such equipment, based on the Rankine cycle, is marketed in small quantities by the Israeli of Ormat Turbines, Ltd., and is under intense development in this country by the Thermoelectron Corp., and Barber-Nichols Engineering, Inc., to name only a few.

Bottoming a Rankine-cycle engine to the MIUS heat recovery system is ideally suited to the properties of organic working fluids. At significantly higher heat addition temperatures, thermal decomposition often becomes a serious problem.

An interesting amalgam of the bottoming waste-heat recovery engine and solar energy is the solar and waste-heat bottoming Rankine-cycle engine. Through this hybrid power generation system, economic predictions unfavorable to each concept taken alone may possibly be turned into a feasible system concept. The rationale for this conclusion is based on the sharing of common pieces of equipment which would have otherwise been amortized against a single application. The solar and waste-heat hybrid power generation system is shown schematically in Figure 3.3.5.

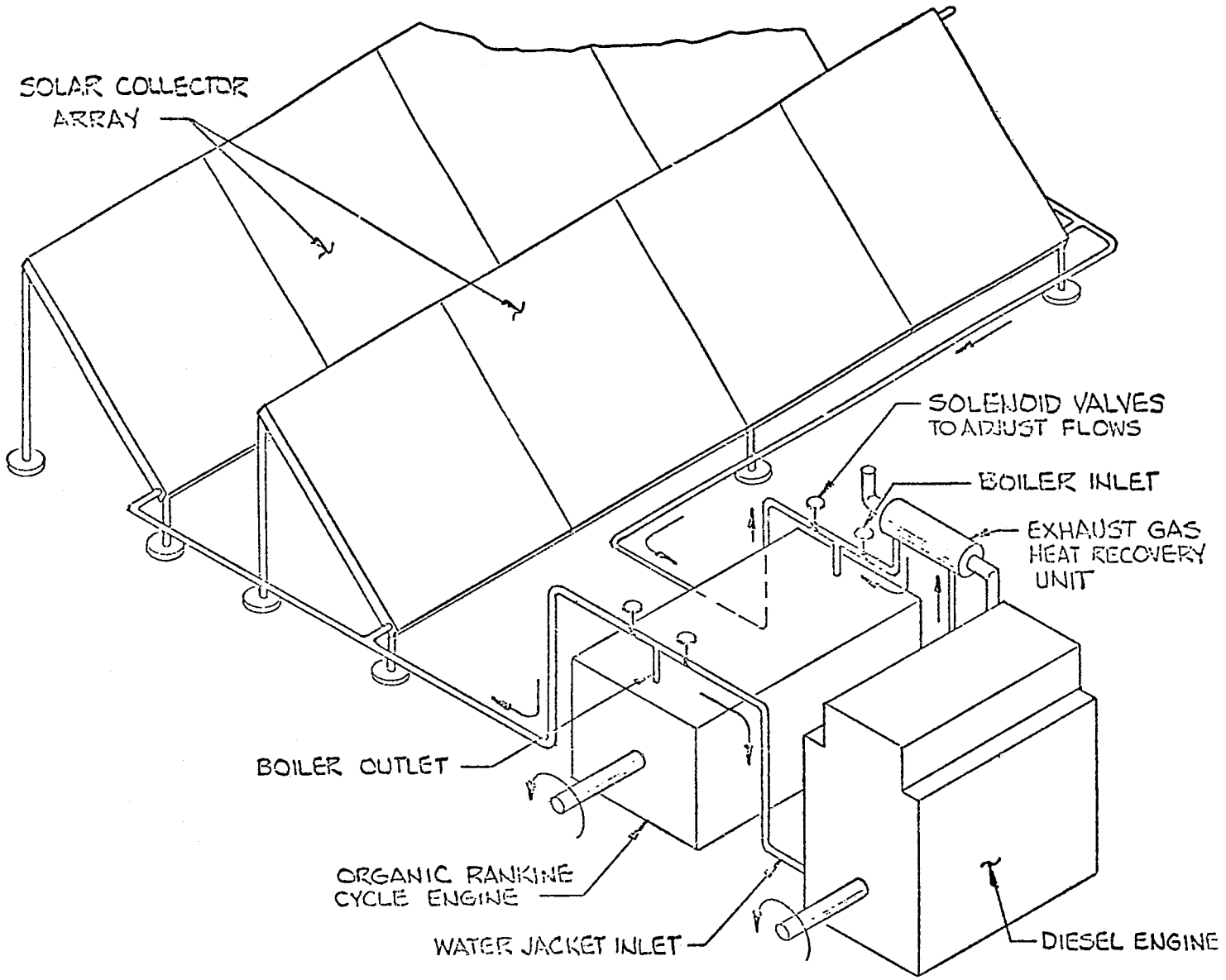


FIGURE 3.3.5 SCHEMATIC OF SOLAR-BOTTOMING RANKINE POWER SYSTEM

3.3.3 Performance Characteristics of Solar Power Generation Concepts

Figure 3.3.6 outlines several important operating characteristics of solar-powered Rankine-cycle engine systems. The component efficiencies given in this figure are roughly those found from system optimization studies. This process is explained with the aid of Figure 3.3.7.

System energy conversion efficiency, η_{sys}, is the performance index which describes the amount of energy delivered by the solar power generation system for each unit of solar energy incident on the collector panels. It is comprised of two components: engine thermal efficiency, and collector panel efficiency. As may be seen in Figure 3.3.7, engine efficiency - the ratio of work delivered by the engine to the useful collected solar energy - increases with solar collector temperature. On the other hand solar collection efficiency - the ratio of useful collected heat energy to incident solar energy - falls with collector temperature increases. As a consequence, there is an optimum operating collector temperature which maximizes the system energy conversion efficiency. This temperature ranges roughly between 200°F and 400°F, depending on equipment performance levels and environmental conditions.

3.3.3.1 Solar-Heated Rankine-Cycle Engine Water Pumping Power

Figure 3.3.8 provides the hourly power loads from the waste-water and potable water treatment plants. The average load is seen to be about 600 kW, which amounts to 5.3×10^6 kW-Hrs annually for continuous pump operation.

We have examined solar Rankine-cycle engine operating characteristics utilizing advanced technology equipment, and have arrived at the performance evaluations summarized in Table 3.3.1. As may be seen, over one-half the load can be met by this system, but 10 acres - or all the unstructured land in the Village Center - is required. The solar heat cost is significant: $34.5 per million BTU of solar energy delivered as work, or, equivalently, about 12¢/kW-Hr. These estimates are partially founded on our data bases created from previous computer simulations of similar situations; other conditions assumed in the analyses are indicated in Table 3.3.2.

3.3.3.2 Solar-Heated Rankine-Cycle Power Generation

Using the same data base as indicated above, the performance characteristics of a pure solar-powered Rankine-cycle engine were evaluated. The results of the study are to be found in Table 3.3.2. As shown, 35 acres of land - or all the unstructured plus park land in the Village Center - are required for about 10 million kW-Hrs of annual power. This amounts to approximately 8% of the annual MIUS electrical load.

FIGURE 3.3.6

TECHNICAL CHARACTERISTICS OF

SOLAR-POWERED RANKINE CYCLE ENGINE SYSTEMS

- Temperature of heat source : Higher than 180°F
- Working Fluids : Organic and common refrigerants
- Power output : 1 HP and above
- Efficiencies
  - Engine thermal efficiency : 16-23% increasing with source temperature
  - Solar collection efficiency : Approx 50%, decreasing with source temperature
  - System efficiency : 7-11% depending on solar collector
- Heat rejection options : Water cooling preferred
  air cooling feasible
- Load characteristics : Variable without thermal storage
  auxiliary will be required

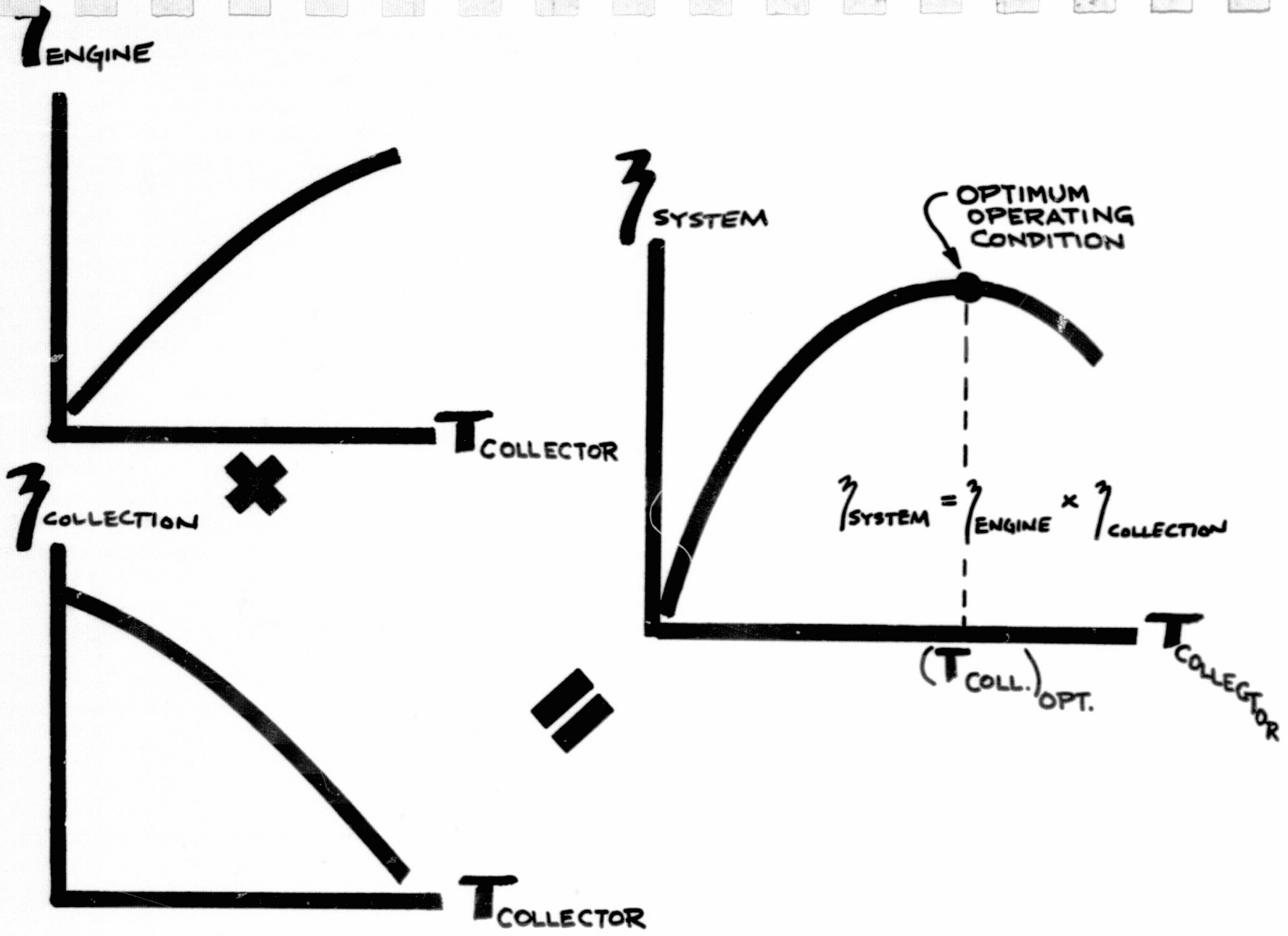


FIGURE 3.3.7

OVERALL RANKINE-CYCLE EFFICIENCY VS. SOLAR COLLECTION TEMPERATURE

FIGURE 3.3.8

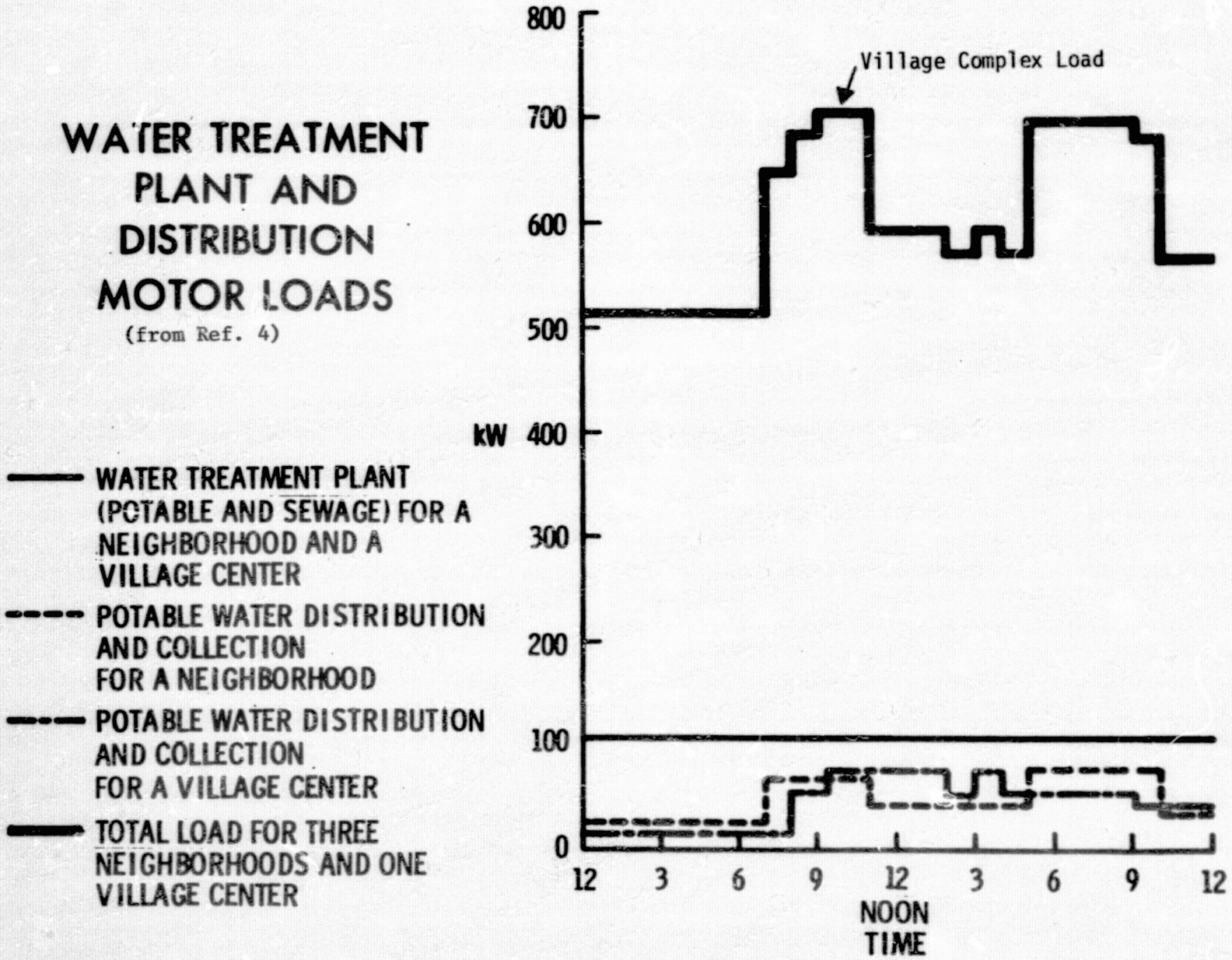

WATER TREATMENT PLANT AND DISTRIBUTION MOTOR LOADS
(from Ref. 4)
WATER TREATMENT PLANT (POTABLE AND SEWAGE) FOR A NEIGHBORHOOD AND A VILLAGE CENTER
POTABLE WATER DISTRIBUTION AND COLLECTION FOR A NEIGHBORHOOD
POTABLE WATER DISTRIBUTION AND COLLECTION FOR A VILLAGE CENTER
TOTAL LOAD FOR THREE NEIGHBORHOODS AND ONE VILLAGE CENTER
Village Complex Load
800
700
600
500
kW
400
300
200
100
0
12
3
6
9
12
3
6
9
12
NOON
TIME

TABLE 3.3.1

APPLICATION: SOLAR-HEATED RANKINE CYCLE ENGINE: WATER PUMPING POWER

ANNUAL LOAD: 53 x 10^6 KW-HRS(1)

CONCEPT	SOLAR COLLECTOR: TEMP LEVEL & DUTY	SOLAR COLLECTOR: TYPE	SOLAR COLLECTOR: AREAS(2)	IMPACT ON MIUS	TECHNOLOGY STATUS	ECONOMIC CONSIDERATIONS(3)
Rankine Engine dedicated to Potable and Waste Water pumping power requirements	350°F Continuous	Water Coolant Advanced Technology	218,000 ft^2 Collector, or 10 Acres of Land. (Based on 0.0037 Land Acres/MW-HR/YR)	Reduce size of prime mover and lower diesel fuel consumption	Engine under development Collectors under development Complex interfaces No system operational experience	Incremental Solar Capital Cost ≅ $34.5/MMBTU of Solar Energy Delivered as Work ($8.0/MMBTU Collected but not Converted)

(1) Conditions: A) Average Power Requirement (from Fig. 3.3.8); B) Duty same each day of year.

(2) Conditions: A) Washington, D.C., Area; B) Advanced Technology Equipment; C) Cooling Tower Heat Sink; D) 100% Gear Box Conversion Efficiency; E) 52% of Load met by solar Rankine-Cycle Engine; F) Land Area ≅ 2 x Collector Area

(3) Conditions: A) Cost of Rankine-Cycle engine subsystem = $250/KW, installed; B) Cost of Solar Collection subsystem = $11/$ft^2$; C) Amortization of Capital Costs Rate = 10%/YR; D) 0.27 MW (Peak)/Land Acre; E) Annual Rankine-Cycle engine efficiency = 23%.

TABLE 3.3.2

APPLICATION: SOLAR HEATED RANKINE CYCLE ENGINE: PURE SOLAR POWER GENERATION

ANNUAL LOAD: 120×10^6 KW - HRS (1)

CONCEPT	SOLAR COLLECTOR TEMP LEVEL & DUTY	SOLAR COLLECTOR TYPE	SOLAR COLLECTOR AREAS(2)	IMPACT ON MIUS	TECHNOLOGY STATUS	ECONOMIC CONSIDERATIONS(3)
Generate Grid Power Using Rankine-Cycle Engines Dedicated to Solar Heat Source	350°F Variable	Advanced Technology	0.0036 Land Acres/MW-HR/YR, e.g., 35 Acres $\cong 10 \times 10^6$ KW-HRS	Reduce Size of Prime Mover and Lower Diesel Fuel Consumption	Engine Under Development Collectors Under Development Complex Interface with Power Grid No System Operational Experience	Incremental Solar Capital Cost $\cong$ \$34.5/MMBTU of Solar Energy Delivered as Work (\$8.0/MMBTU Collected but not Converted

(1) Condition: Total Electrical Load from Figure 1.2.5

(2) Conditions: A) Washington, D.C., Area; B) Advanced Technology Equipment; C) Cooling Tower Heat Sink; D) Land Area $\cong$ 2x Collector Area.

(3) Conditions: A) Cost of Rankine-Cycle Engine Subsystem = \$250/KW, Installed; B) Cost of Solar Collection Subsystem = \$11/ft^2: C) Amortization Rate = 10%/YR; D) 0.27 MW (Peak)/Land Acre; E) Annual Rankine-Cycle Engine Efficiency = 23%

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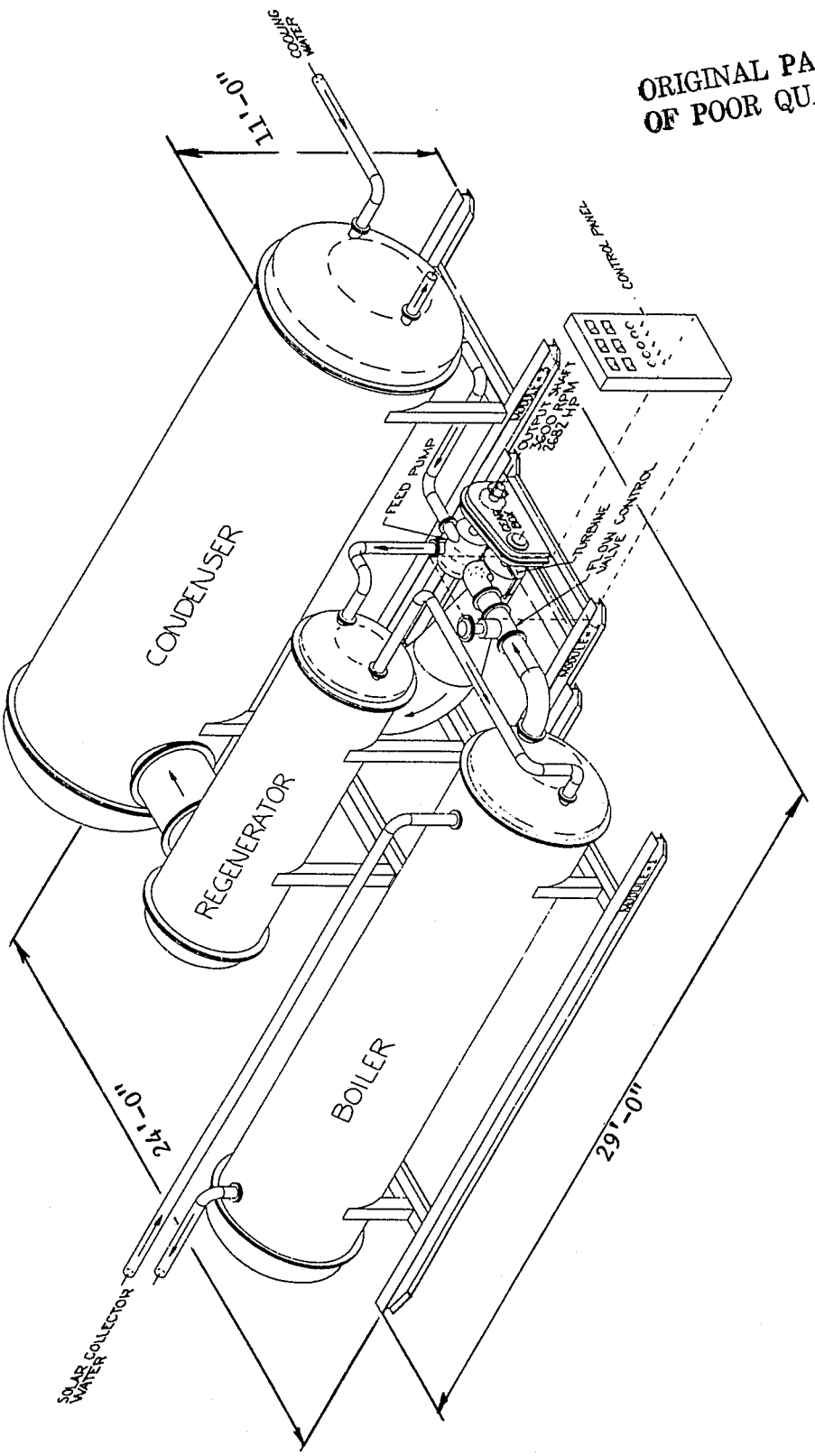


FIGURE 3.3.9 EXAMPLE CONFIGURATION OF CONCEPTUAL 2 MW RANKINE-CYCLE ENGINE PACKAGE

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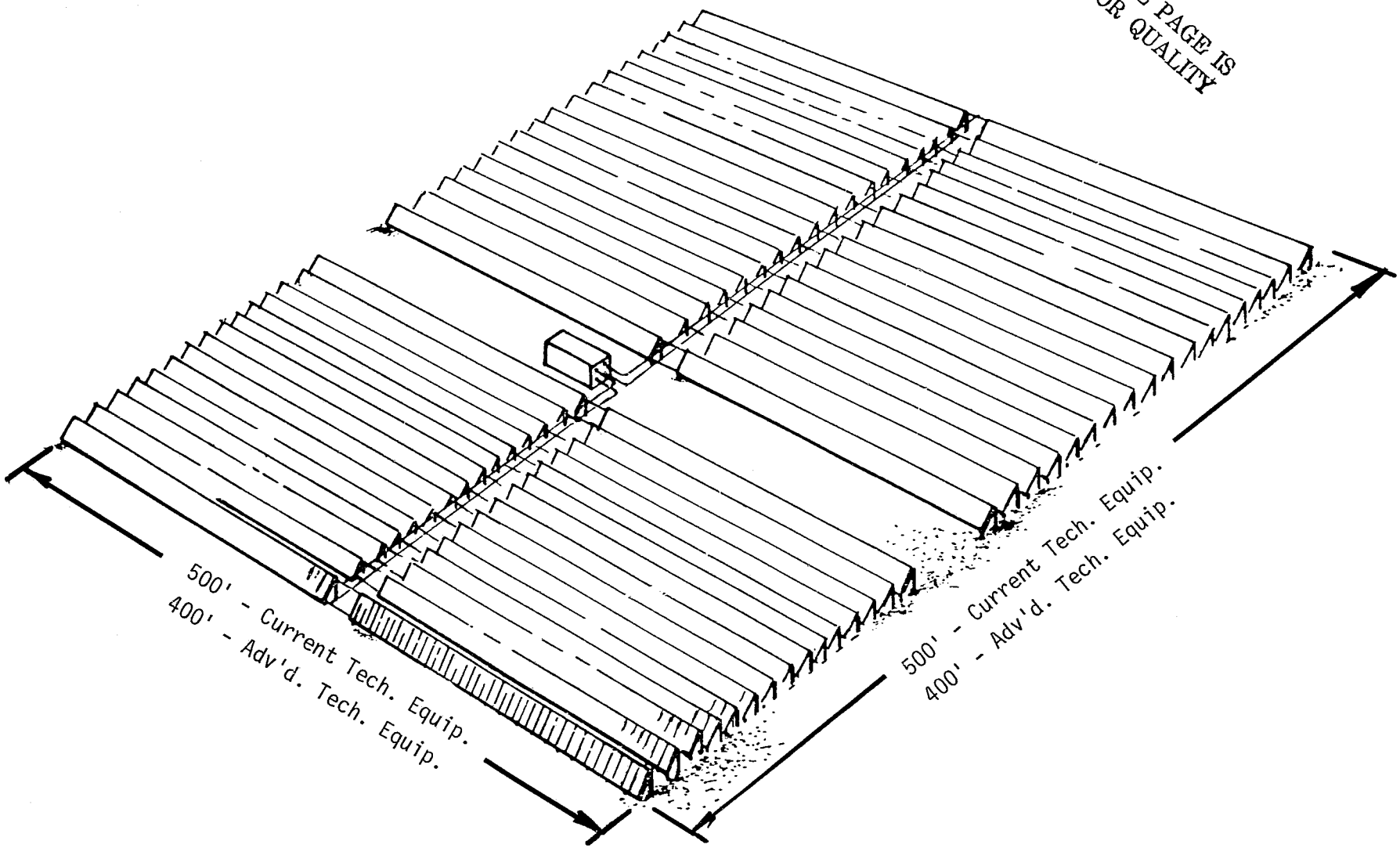


FIGURE 3.3.10 ARTIST CONCEPT OF 1 MW SOLAR POWER MODULE FOR RANKINE-CYCLE ENGINE

TABLE 3.3.3

APPLICATION: SOLAR-HEATED RANKINE-CYCLE ENGINE: COMBINED SOLAR-WASTE HEAT BOTTOMING POWER GENERATION

ANNUAL LOAD: 120×10^6 KW-HRS (1)

CONCEPT	SOLAR COLLECTOR			IMPACT ON MIUS	TECHNOLOGY STATUS	ECONOMIC CONSIDERATIONS(3)
	TEMP LEVEL & Duty	TYPE	AREAS(2)			
Generate Grid Power Using Hybrid Solar Waste Heat Bottoming Rankine-Cycle Engine	350°F Variable	Current Technology Advanced Technology	0.0037 Land Acres/MW-HR/YR of Solar Contribution	Reduce Size of Prime Mover and Lower Diesel Fuel Consumption Increase System Efficiency by Utilizing More Waste Heat Exhaust Temperature will have to be adjusted to Optimize Overall System Efficiency	Engine Under Development Collectors Under Development Complex Interface with Power Grid No System Operational Experience	Incremental Solar Capital Cost $\cong$ \$34.5/MMBTU of Solar Energy Delivered as Work Incremental Waste-Heat Capital Cost = 0.67 - 0.86¢/KW-HR of delivered work

(1) Condition: Total electrical load from Figure 1.2.5

(2) Conditions: A) Washington, D.C., Area; B) Advanced Technology Equipment; C) Cooling Tower Heat Sink; D) Land Area $\cong$ 2x Collector Area

(3) Conditions: A) Cost of Rankine-Cycle Engine Subsystem = \$250/KW, Installed; B) Cost of Solar Collection Subsystem = \$11/ft^2; C) Amortization Rate = 10%/YR; D) 0.27 MW (Peak Solar Power)/Land Acre; E) Rankine-Cycle Engine Efficiency = 23%; F) Barber, R.E., "Rankine Cycle Systems for Waste Heat Recovery," Chem. Eng., Nov., 1974.

In these preliminary analyses, cost differences between direct-shaft power production and grid electrical production were not considered since these differences tend to be small in comparison with the costs associated with the solar collection subsystem. Consequently, the solar heat cost of grid power generated by advanced technology solar equipment is about $34.5 per million BTU of delivered work, or equivalently, about 12¢/kW-Hr.

Figure 3.3.9 provides a view of the component arrangement and approximate overall dimensions for a 2 MW (Peak) Rankine-cycle engine power package. In Figure 3.3.10 we may see the overall dimensions and arrangement of the solar collector array designed for 1 MW of peak power; two of these would be required for each power package of Figure 3.3.9.

3.3.3.3 Combined Solar and Waste-Heat Bottoming Rankine-Cycle Engine Power Generation

For the purposes of this initial course screening of concepts, we will not consider reconfiguring the prime movers to accommodate the extra power produced by the solar and waste-heat bottoming power generator. As a consequence, the minimum energy-production im impact of this hybrid engine can be readily estimated from simple relationships.

At the end of each year, the Village Complex MI MIUS leaves unused 156,729 million BTU of recovered heat (see Figure 1.3.2). It will be recalled that this heat is recovered in the form of 240°F low-pressure steam. The work recoverable from this waste heat can be computed from:

$$W = \varepsilon \, \eta_c \, Q_w = \varepsilon \left(\frac{1-T_{ambient}}{T_{waste\ heat}}\right) Q_w$$

where Q_w is the available waste heat, η_c is the Carnot thermal efficiency based on the waste-heat temperature and ambient heat rejection temperature, and ε represents the fraction of Carnot efficiency attained by the bottoming Rankine-cycle engine. Assuming an ambient temperature of 80°F, the Carnot efficiency is approximately 23%. For advanced technology Rankine-cycle engines, ε may approach 0.68. Therefore, the annual bottoming cycle work from the above equation is approximately 7.2×10^6 kW-Hrs, or about 6% of the Village Complex's power needs.

Although the waste heat is free, the power generation system is not, of course, so that the capital investment in equipment must be amortized annually on the basis of the total energy produced and the cost of capital. Published data [7] indicates the total generating costs of waste heat to be between 0.673 and 0.859¢/kW-Hr. If the value of electricity is 3¢/kW-Hr, the payoff period for the equipment is approximately 1 year.

The solar portion of the hybrid power generation system can be analyzed on a first-order basis by assuming the solar

operation is independent of the bottoming power production system. As a result, the land area impact and solar heat cost estimates presented in Table 3.3.2 can be applied here. These values are repeated in Table 3.3.3. Once again, for an advanced technology solar collection and energy conversion system to contribute 9.6×10^6 kW-Hrs/Yr to the 120×10^6 kW-Hr annual MIUS energy load (approximately 8%), 35 acres of land is required in the Village Center. This is equal to all the park plus unstructured land in the Village Center.

3.4 Heating, Ventilation, and Air Conditioning Subsystems

3.4.1 Subsystem Requirements

The MIUS space conditioning subsystems provide domestic hot water, space heating, space cooling, and--as a part of the cooling function--dehumidification. The energies expended to accomplish these functions are primarily electrical energy for the detached single family houses (electrical resistance domestic hot water, heat pump heating and cooling), and thermal energy in the remaining buildings of the complex. The central HVAC subsystem supplies hot water in the range of 170-200°F, and chilled water at a temperature near 45°F.

The electrical energy required for the single family space conditioning function is supplied upon demand, with winter or summer peaking demands occurring during very cold or very hot weather. In the MIUS configuration examined in this work, waste heat from the power generating equipment and solid waste incinerator supplies thermal energy to the HVAC subsystem at the 170°-200°F level for space heating, or at the 240°F level to drive absorption chillers to provide the 45°F water for space cooling and dehumidification. In the event that insufficient waste heat is available to the absorption machines, electric vapor-compression machines are used to supplement the absorption refrigeration. Table 3.4.1 displays approximate values of the annual loads for the various buildings in a Village Complex. The loads are given for each function on an individual building basis as well as for the entire complex. As illustrated in the table, the total domestic hot water and space heating loads for all the single family dwellings are larger than the hot water and heating loads for the remaining buildings in the Village Complex. In addition, as discussed above, the space conditioning functions in the single family dwelling are accomplished at the direct expense of electrical energy. Hence, the single family units are prime candidates for energy savings accomplished by solar thermal energy systems. In the remaining buildings, the hot water, space heating and cooling loads are dominant, largely because of the large sensible and latent heat contributions from buildings occupants. The loads shown in the table were estimated from the average heating and cooling seasonal load profiles presented for each building.

Subsequently, updated loads were received from the Urban Systems Project Office. These are summarized in Table 3.4.2, where they are compared with the load values estimated earlier. The comparison is shown here because the preliminary concept evaluation was carried out on the basis of the earlier estimated loads.

TABLE 3.4.1

Estimated Annual Loads

Location	Building	No. of Units	Individual Unit Annual Loads (10^6 BTU)			Complex Annual Loads (10^6 BTU)		
			HW	Heat	Cool	HW	Heat	Cool
Neighborhood*	Single Family	713	32	58	22	67,379	124,062	46,202
	Town House	324	32	47	20	31,104	45,684	19,829
	Garden Apts.	324	15	34	41	14,580	32,659	39,560
	Elem. School	1	339	311	880	1,020	934	2,639
Village Center	High School	1	2,267	501	4,000	2,267	501	4,000
	Middle School	1	2,267	561	3,827	2,267	561	3,827
	High Rise Apts.	6	1,405	470	634	8,430	2,820	3,801
	Commercial Center	1	129	864	4,029	129	864	4,029
	Recreational Center	1	307	432	1,985	307	432	1,985

*Three per Village Complex

TABLE 3.4.2

Comparison Between Early Estimated Loads and Updated Loads Furnished by NASA

Building	Estimated Loads (10^9 BTU) HW	Heat	Cool	Updated Loads (10^9 BTU) HW	Heat	Cool
Single Family	67.4	124.1	46.2	68.4	118.6	45.1
Townhouse	31.1	45.7	19.8	31.2	42.4	23.8
Garden Apts.	14.6	32.7	39.6	14.6	15.1	20.6
Elementary School	1.0	0.9	2.6	1.0	1.2	3.4
High School	2.3	0.5	4.0	2.3	0.8	4.6
Middle School	2.3	0.6	3.8	2.3	0.8	4.0
High Rise Apts.	8.4	2.8	3.8	8.4	17.0	21.0
Commercial Center	0.1	0.9	4.0	0.1	1.4	4.4
Recreational Center	0.3	0.4	2.0	0.3	0.4	2.3

For the most part, the agreement between the early estimated and updated loads is quite close. Exceptions occur for the garden apartments--where the updated heating and cooling loads are lower by about 50%--and for the high rise apartments--where the heating and cooling loads are higher by a factor of about six. However, even these large differences do not alter the conclusions that will be developed in the paragraphs below concerning the effectiveness of the various solar heating and cooling applications in the MIUS.

3.4.2 Descriptions of Solar Space Conditioning Concepts

Solar space conditioning subsystems may be potentially used to meet any or all of the four HVAC system functions--domestic hot water, space heating, space cooling and dehumidification. The subsystems may be located on-site for each application, in "solar substations" for a cluster of buildings--using the existing water network or using a parallel network connecting the individual buildings to the solar substation, or in a "central" location, providing hot or chilled water to the existing MIUS 4-pipe HVAC network. Table 3.4.3 presents a comparison between the characteristics of individual and central solar systems. In general, individual units would tend to be less sophisticated, have lower performance, and require no additional land area other than roof area: central units would tend to be higher performance, more sophisticated and would require additional land area.

The design of the solar climate control subsystems would depend on the function intended to be served and the location. Figure 3.4.1 illustrates a concept for solar water heating with electric resistance backup--a system suitable for the MIUS single family residence. As illustrated, the solar system may either be a pre-heat system--where the solar heated water is supplied to an existing electric water heater tank, or an integrated system where the solar thermal storage tank and the "conventional" hot water tank are the same. Some of these designs trade-offs will be discussed in greater detail below.

Figure 3.4.2 illustrates a system arrangement suitable for domestic hot water and space heating in a MIUS single-family dwelling using a heat-pump as an auxiliary unit. There are many possible solar heat-pump systems arrangements; the system illustrated in the figure is only shown as an example arrangement. The heat pump provides a backup to the solar system in the heating mode; it is also used to accomplish space cooling in the summer months.

Figure 3.4.3 illustrates a solar generated hot water, heating and cooling system concept suitable for use in individual buildings that otherwise receive their space conditioning by use of the MIUS 4-pipe HVAC distribution network. Solar domestic water heating and space heating is accomplished in the same fashion as in the solar systems for the single family units; solar cooling is accomplished by

TABLE 3.4.3

CHARACTERISTICS OF INDIVIDUAL AND CENTRAL SOLAR

COLLECTION FOR SPACE CONDITIONING

Individual	Central
• Smaller units	• High-performance collectors required to provide - 170°F water for hot water or space heating to be compatible with MIUS waste heat - 210-250°F water to drive refrigeration equipment (absorption cycle, rankine heat engine)
• Less sophisticated design	• Best suited for air conditioning function
• Low temperature operation sufficient for hot water and space heating	• Install on ground in open areas
• Most suitable for relatively low buildings	• Tracking feasible
• Install on roofs	• Large system provides some economy of scale
• Collectors may not be oriented in optimum direction	• Large thermal storage can alleviate peaking problem
• Collectors stationary	

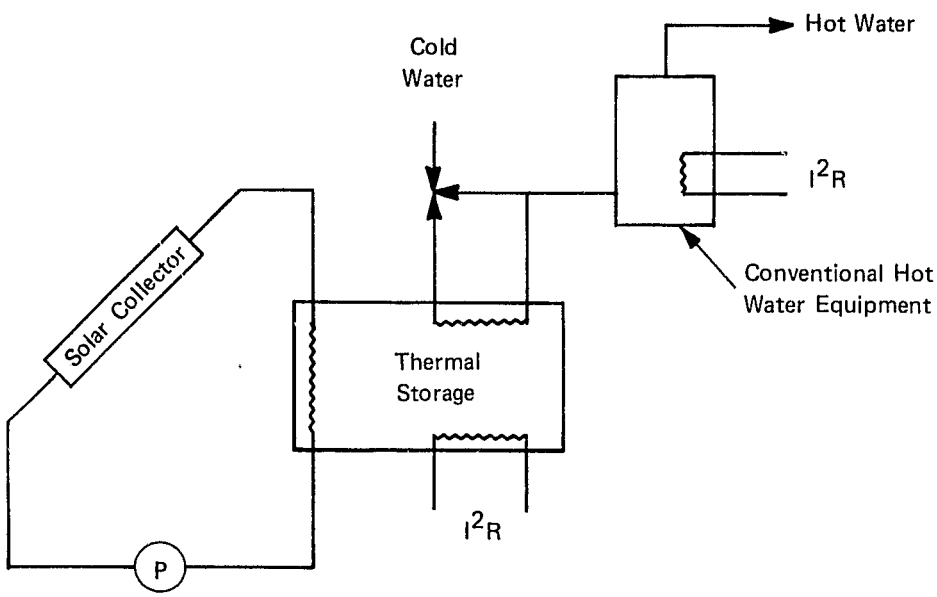
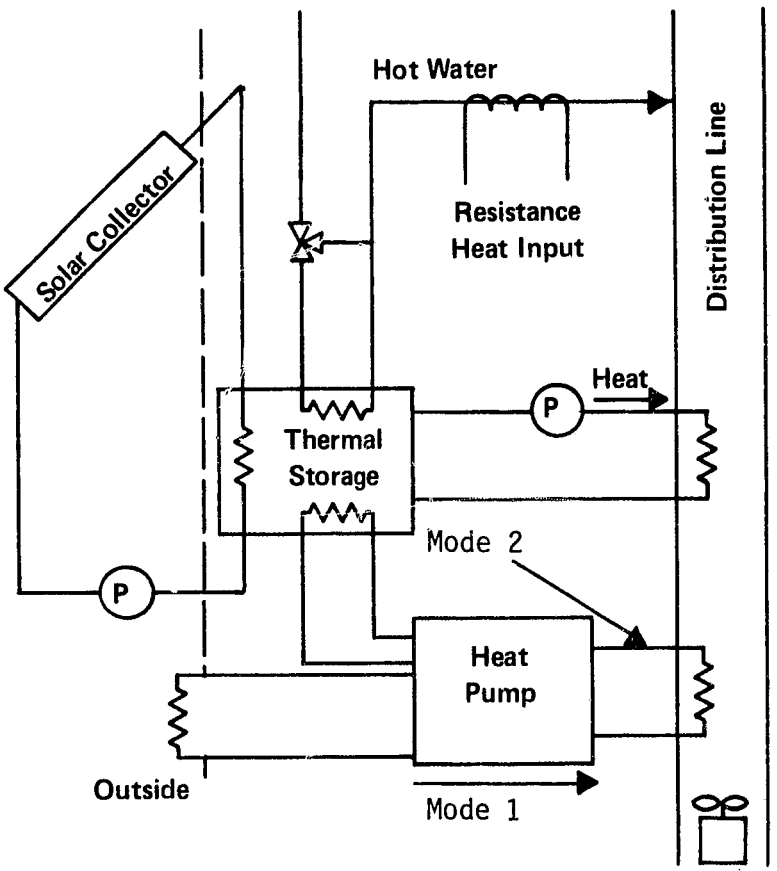


FIGURE 3.4.1

SOLAR DOMESTIC HOT WATER INTEGRATED WITH ELECTRIC RESISTANCE HEATING

FIGURE 3.4.2

SOLAR HEATING WITH HEAT PUMP AUXILIARY



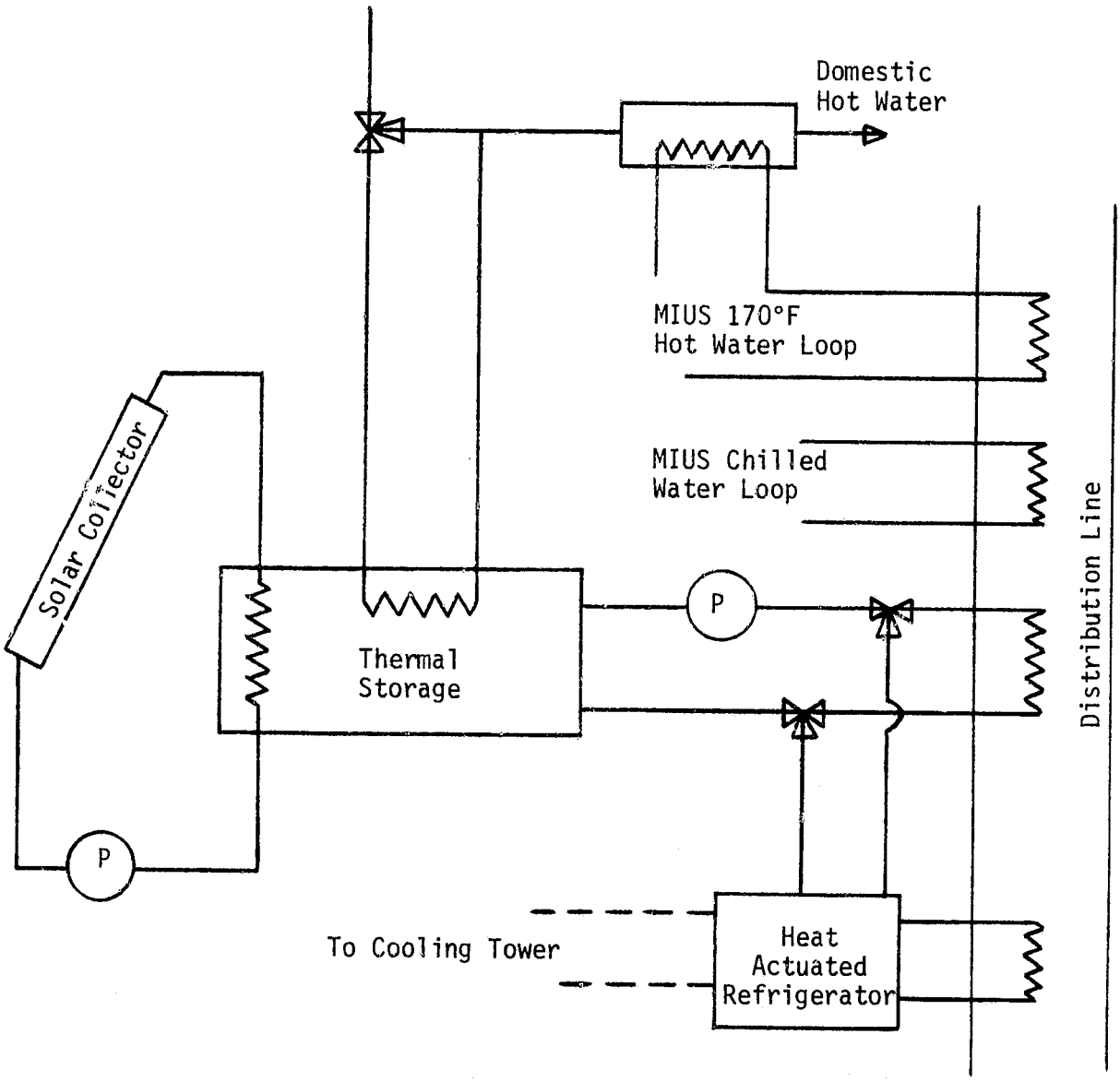


FIGURE 3.4.3

ON-SITE SOLAR HOT WATER, HEATING AND COOLING

IN MIUS BUILDINGS ON 4-PIPE DISTRIBUTION NETWORK

use of an on-site heat actuated refrigeration machine, such as an absorption machine or a heat-engine driven vapor-compression machine. The chilled water also accomplishes removal of moisture within the conditioned space, thereby maintaining a controlled humidity level.

In applications where the dehumidification load is expected to be large, solar activated dessicant systems might be employed to partially meet the latent load. A number of systems arrangements are possible, including liquid absorbent spray systems and solid desiccants used in either rotary or fixed bed configurations. To a first approximation, any of these units can be considered as a "black box" replacement for the "heat actuated refrigerator" shown in Figure 3.4.3, except that a portion of the solar dehumidifier operater in the distribution line, and a source of regeneration air is required. Typically, solar dehumidification systems require regeneration temperatures ranging from 150°F to 250°F and have coefficients of performance ranging from 0.5 to 0.8. The liquid systems require cooling towers; the solid desiccants may be cooled by regeneration air.

The major components of a central solar thermal system are the same as those illustrated in the previous diagrams--solar collectors, a thermal storage subsystem, controls, and a distribution network. Figure 3.4.4 illustrates how a central system would be integrated with the MIUS 4-pipe HVAC system distribution network. In this arrangement, the solar system would supplement the waste heat from the MIUS prime movers to provide hot water for domestic water or space heating, or to drive the absorption cooling units. Since the prime movers will always provide waste heat, the central solar system will never meet the entire load. Hence, the storage subsystem will be more complex than with the individual applications; they will be required to accept heat at higher temperatures, and may even be employed for storage of waste heat. That is, the solar system may provide additional possibilities for load management.

Generally, in the central collection application, the solar systems must provide heat at higher temperatures than required in individual applications. Hence, the use of high performance collectors* will be required. In addition, tracking may also be a requirement to achieve cost-effective solar collection. This will be examined in more detail below.

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* see Figure 1.4.2 for a comparison between high performance ("advanced technology") collectors, and intermediate and baseline collectors.

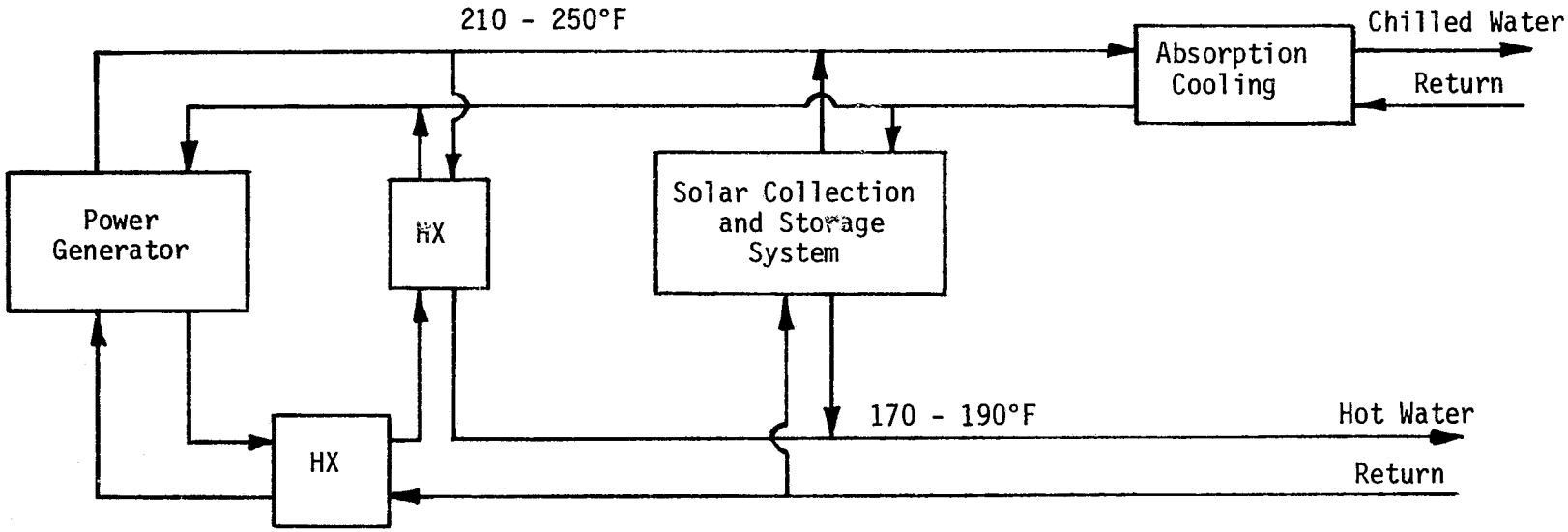


FIGURE 3.4.4

CENTRAL SOLAR COLLECTION AND DISTRIBUTION

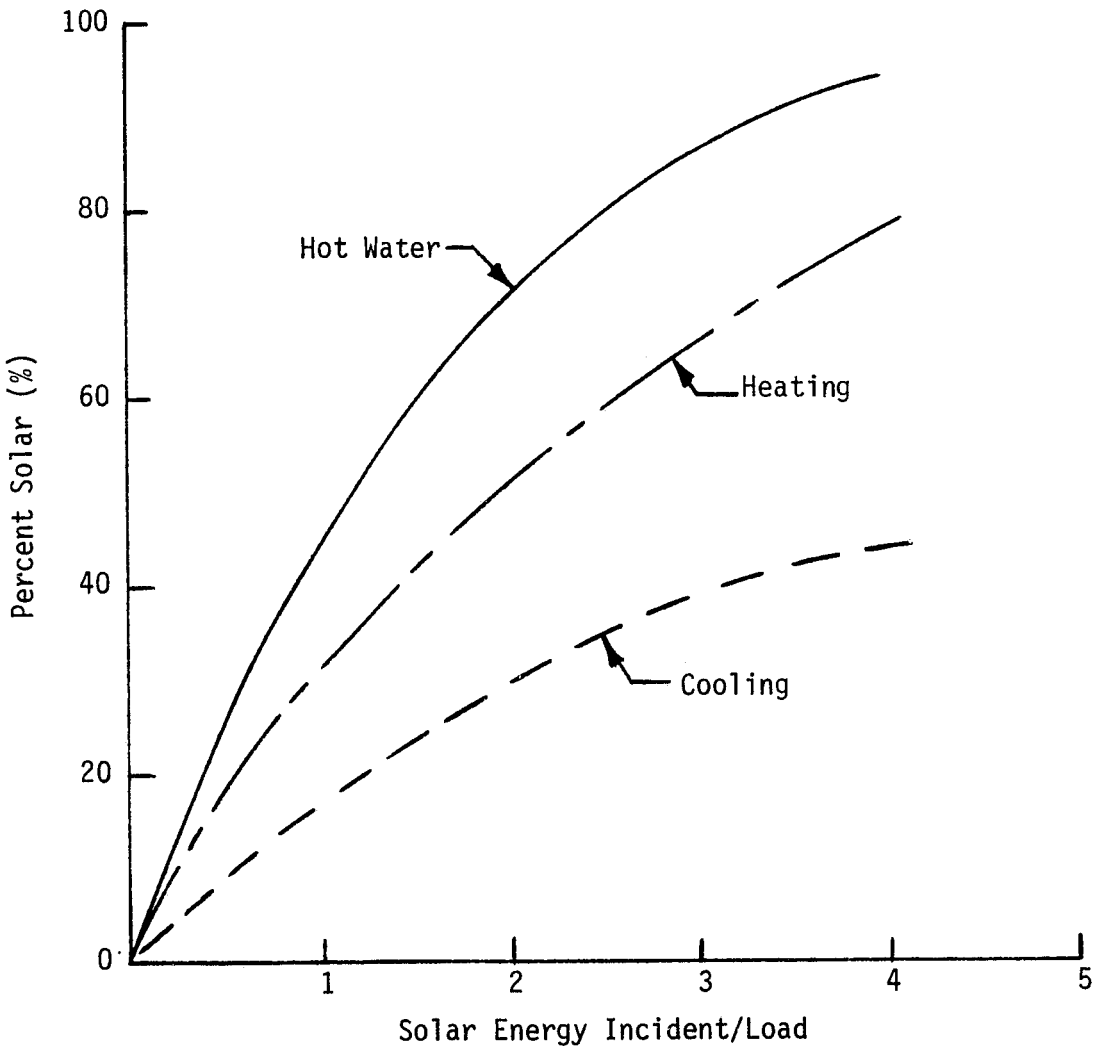


FIGURE 3.4.5

PERFORMANCE CURVES FOR BASELINE COLLECTOR

TABLE 3.4.4

WORKING EQUATIONS FOR RELATIONSHIPS

"Solar Energy Incident/Load" = Q_i/Load

= (Q_i/A) (A/Load)

= $\left(\frac{1}{\bar{\eta}}\right)$ (Q/Load)

= $(\%S)/(100\bar{\eta})$

Q_i = Yearly sun energy incident on solar collector

Q = Annual solar energy collected and utilized

A = Area of solar collector

Load = Annual thermal energy that must be supplied to satisfy building's climate control requirements. For hot water or heating this is equal to the annual demand; for cooling, it is the thermal energy that must be supplied to a heat actuated machine--equal to the cooling load divided by the COP.

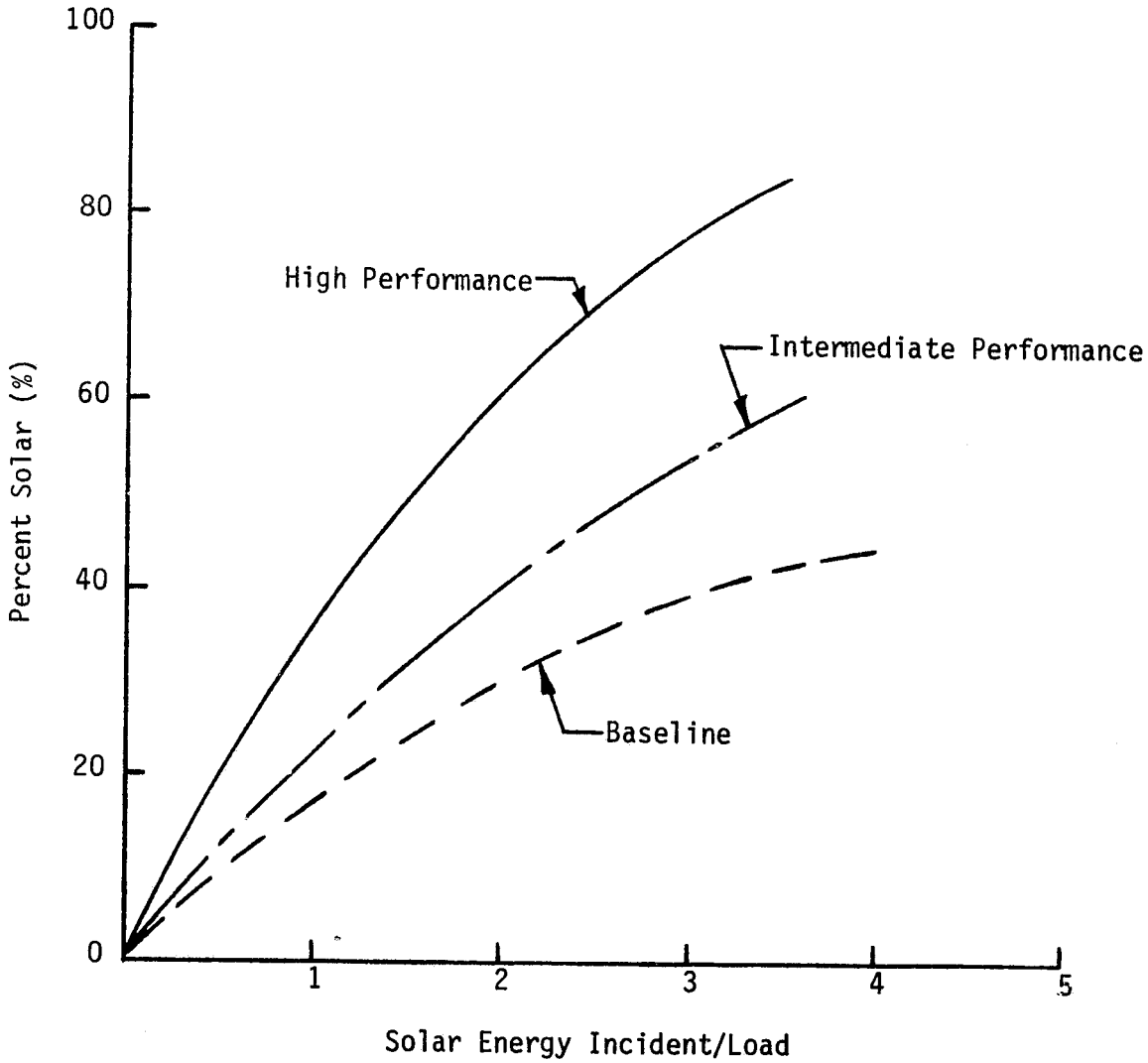


FIGURE 3.4.6

PERFORMANCE CURVES FOR COOLING APPLICATION

3.4.3 Performance Characteristics of Solar Space Conditioning Concepts

From our earlier work on related projects, we have been able to develop general relationships that can be used to approximate the behavior of solar systems for various functions. Figure 3.4.5 illustrates such a relationship for the baseline collector in terms of the percent solar index and a parameter "solar incidence per unit load". This later parameter is simply the ratio of the annual solar energy incident on the collector to the total annual load. Table 3.4.4 shows the relationship between this parameter and the percent solar and system efficiency parameter. The solar energy incidence per unit load parameter is a measure of the size of the solar system relative to the load.

Correlations are shown separately for the hot water function, heating function and cooling function. They differ because of differences in temperature levels required to achieve the functions and because of the seasonality of the load. It must be emphasized that these correlations are only approximate--they are primarily useful for determining the relative size of a system to meet a certain percentage of the load. They will vary somewhat with geographic location and with building type because of weather differences and individual characteristics of a load.

Figure 3.4.6 illustrates another set of relationships for various collector types used to drive absorption chillers. The curves show clearly why high-performance (advanced technology) collectors should be used for space cooling application.

When carrying out the preliminary performance analyses of candidate solar concepts, we made use of our existing data base, as represented by the curves in Figure 3.4.5. As noted above, these curves provide a relationship between collector area annual insolation*, percent solar and annual system efficiency. These parameters will be used in the following discussions of the various candidate solar space conditioning concepts.

3.4.3.1 Low-Density Applications

Tables 3.4.5 to 3.4.7 summarize the evaluation of solar generated hot water, heating, and cooling in the single family detached residences. For hot water heating we will examine

---

* annual insolation on titled collector in Washington D.C. $= Q_i/A \cong 0.56 \times 10^6$ Btu/ft^2

TABLE 3.4.5

APPLICATION SINGLE FAMILY DETACHED-HOT WATER ONLY

ANNUAL LOAD 31.5x10^{6}BTU/bldg; 67,379x10^6 BTU/complex

CONCEPT	COLLECTOR TEMP LEVEL	COLLECTOR TYPE	COLLECTOR SIZE (ft^2)	IMPACT ON MIUS	TECHNICAL STATUS	POTENTIAL ECONOMICS
1. Individual unit on roof	100-150°F	Flat, base-line or selective surface	100*	Reduce I^2R by about 12,000 mw-hrs/yr	Current	SHC ≃ $8-10/10^6 BTU ≃ 2.7-3.4¢/kwh
2. Centralized for cluster of houses (typically 18) †	120-170°F	Flat, selective surface or advanced	1,500*	Reduce elec demand; require piping to individual houses	More complex controls; current technology	Good if combined with space heating

* Sized to meet 50-60% of load

† Collectors would be on-ground in unused open area

NOTE: Judgements above based on ADL data base.

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Table 3.4.6

APPLICATION SINGLE FAMILY DETACHED-HOT WATER AND HEAT

ANNUAL LOAD 31.5/58x10^6/bldg; 67,379/124,062 x10^6/complex

CONCEPT	TEMP LEVEL	COLLECTOR TYPE	SIZE (ft^2)	IMPACT ON MIUS	TECHNICAL STATUS	POTENTIAL ECONOMICS
1. Individual solar plus air-air heat pump	100-150°F	Baseline or selective	300*	reduce elec demand by ≃ 19,000 mw-hrs.	Current	SHC ≃ \$10-12/10^6 BTU
2. Individual solar pre-heating water-to-air heat pump	100°F	Baseline or selective	300†	≃ 18,000 mw-hrs.	Current	SHC ≃ \$9-11/10^6 BTU
3. Centralized for cluster of houses; pipe hot water; individual air-air heat pump suppl	140-160°F	Selective or Advanced	5,000*	Reduce elec demand by 19,000 mw-hrs require pipe network	Expected in 1-2 years	Probably not as good as case 1; say, \$12-14/10^6 BTU
4. Centralized with heat input to firewater distribution network, water-air heat pump	100-120°F	Selective surfaces	5,000▲	Reduce elec demand for space heating only (6,000 mw-hrs)	Current	Heating only (no hot water) SHC ≃ \$18-20/10^6 BTU

* Supply ≃ 70% HW load; 30% heating load; assume SPF of heat pump = 2.0
† Supply ≃ 10% HW load; allow use of water-air heat pump with SPF = 3.0
▲ Supply heating only

Table 3.4.7

APPLICATION: DETACHED SINGLE FAMILY - SPACE COOLING

ANNUAL LOAD: 21.6×10^6/bldg; $46{,}202 \times 10^6$/complex

CONCEPT	TEMP LEVEL	COLLECTOR TYPE	IMPACT ON MIUS	TECHNICAL STATUS	POTENTIAL ECONOMICS
1. Individual -absorption -dessicant -Rankine cycle -nite-time radiative	210°F 190°F 250°F -	Advanced ↓ Baseline with removable cover	Small ↓	In development (1-2 yrs.) -	Very poor; heat pump supplies a/c and is used for winter space heating
2. Centralized pipe chilled water	250°F	Advanced	Small	1-3 yrs.	Poor; not competitive with heat pump

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two concepts: individual units and clustered units. The more promising concept is the individual unit application, which results in a reduction in annual electrical energy demand of about 12,000 MW-HRS. It should be noted that in the analysis, the collectors were sized to meet about 60% of the load. It has been our experience that this percentage provides the most cost-effective collector size for a hot water system.

The Solar Heat Cost (SHC) was calculated assuming an amortization rate equal 10%. From the definition of SHC given in section 3.0, and the relationships shown in Table 3.4.4 a simple expression can be derived that allows the SHC to be calculated directly from Figure 3.4.5:

$$SHC = \frac{100\ R\ (C/A)\ (A/Load)}{\%\ S}$$

For small systems such as individual hot water heating systems, the capital cost per unit area of collector, C/A, was taken to be $\$14/ft^2$ (see Table 2.2.1).

Table 3.4.6 summarizes the evaluation of space heating concepts in single family units. Space heating was accomplished first by the solar system, and then using the heat pump in the backup mode. We examined several ways of interfacing the heat pump and the solar system. The most promising arrangement -- based on current heat-pump technology -- would appear to be the arrangement where the solar system and heat pump are in parallel with one another. (This preliminary judgement was based on our experience in previous analyses of solar/heat pump systems.) The least promising system is one using centralized collection with heat input to the firewater distribution network which would serve as a heat source for a water-to-air heat pump located in the individual residence. In this latter arrangement, the solar system cannot be used to meet the domestic waster load which underutilizes the equipment.

Table 3.4.7 summarizes various approaches to solar cooling in the single family units. None of these concepts are attractive because of high COP conventional heat-pumps and because solar cooling with absorption refrigeration currently requires high-performance solar collectors.

3.4.3.2 High-Density Applications

Tables 3.4.8 through 3.4.10 summarize the characteristics of solar domestic water heating, space heating, and space cooling in the MIUS townhouses. The performance characteristics of solar water heating are about the same as for the single family. However, for the townhouse -- as for all other buildings in the Village Complex that are not single family dwellings -- water heating is done with MIUS waste-heat. Hence, the "value of collected heat", discussed in section 3.0 may not be as large as when the solar energy is displacing electric resistance heat.

We also mention use of an "advanced technology" collector to supply heat directly to the MIUS distribution network. The potential economics of this approach will be dealt with in greater detail in later paragraphs.

Table 3.4.9 shows that the potential SHC economics for solar generated hot water and space heating functions are about the same as for the single family residence; however, in the townhouses, the solar system displaces waste heat rather than electric energy.

As may be seen in Table 3.4.10, the economics of on-site space cooling in the townhouse are unattractive because of the additional capital cost for the refrigeration device, the requirement for high-performance collectors and the relatively "low economic value" of the MIUS supplied chilled water. Central cooling is discussed more fully below.

Table 3.4.11 summarizes the solar collector area required to accomplish water heating, water heating and space heating, or space cooling in the remaining buildings in the Village Complex. The energy savings per complex are also given. The values in the table refer to on-site applications.

Table 3.4.11 also shows that for many of the buildings, insufficient roof area is available to satisfy 50% of the cooling load with an on-site solar system. As an example, about 50,000 ft^2 of collector area is required to meet 50% of the high school cooling load, whereas only 30,000 ft^2 of roof area is available. This suggests that solar cooling of these buildings might best be accomplished in a central location using the existing chilled water distribution network. Alternatively, the building might be a candidate for a more modest solar application, such as solar dehumidification. Table 3.4.12 summarizes as a case example the characteristics of solar dehumidification for the high school. It was assumed in the analysis that the latent heat load equaled 15% of the total cooling load. We briefly examined three types of desiccant systems. The impact on the MIUS is a reduction in the annual chilling load.

Table 3.4.8

APPLICATION: TOWNHOUSE - HOT WATER ONLY

ANNUAL LOAD: 32.0×10^6/bldg; $31,104 \times 10^6$ BTU/complex

CONCEPT	TEMP LEVEL	COLLECTOR TYPE	SIZE (ft^2)	IMPACT ON MIUS	TECHNICAL STATUS	POTENTIAL ECONOMICS
1. Individual units on roof	100-150°F	Baseline or Selective	100	Reduce waste heat demand by ≈ 18,000x 10^6 BTU	Current	SHC $8-10/$10^6$BTU
2. Local cluster of townhouses (8)	170°F	Advanced	700	Reduce waste heat demand; collected solar heat put into pipe network	In development, 1-2 yrs.	Not as good as above, need to collect heat at higher temperature to be compatible with waste heat
3. Increment on central collector. Heat put into pipe distribution system	180°F	Advanced	85,000	← same as above →		

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Table 3.4.9

APPLICATION: TOWNHOUSE - HOT WATER AND HEAT

ANNUAL LOAD: 32.0/47.0x10^6/Bldg; 31,104/45,684x10^6/complex

CONCEPT	TEMP LEVEL	COLLECTOR TYPE	SIZE (ft^2)	IMPACT ON MIUS	TECHNICAL STATUS	POTENTIAL ECONOMICS
1. Individual Units	100-150°F	Baseline or Selective	300	Reduce demand for waste heat by ≈ 35,500 x10^6 BTU	CURRENT	\$10-12/10^6 BTU Displaces MIUS waste heat
2. Central Collection	← Same comments as for hot water only function →					

Table 3.4.10

APPLICATION TOWNHOUSE - SPACE COOLING

ANNUAL LOAD 20.4×10^6 BTU/bld; $19{,}829 \times 10^6$ BTU/complex

CONCEPT	TEMP LEVEL	COLLECTOR TYPE	SIZE * (ft^2)	IMPACT ON MIUS	TECHNICAL STATUS	POTENTIAL ECONOMICS
1. Individual Unit:						
-absorption	210°F	Advanced	300	Supply 0.8×10^6 ton-hours of refrigeration (Save 625 of electrical demand)	Available	Unattractive
-dessicant †	190°F				In development	
-Rankine cycle	250°F					
-nite time radiative	-	Panel w/out cover plate	600		Available	More promising than above
2. Central Collection	230°F	Advanced	200,000	Same as above Potential to reduce size of prime mover	Near Term	Can reduce electrical demand by SHC equivalent to 48¢/kwh

NOTE: Economics can be improved by using solar collectors to also deliver heat for hot water and space heat (discussed separately).

* To meet 50% of load; assume COP - 0.6

† Cycle similar to IGT design where air overdried and subsequently rehumidified to provide cooling

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Table 3.4.13 summarizes the required collector areas to provide 50% of the dehumidification load in the four buildings with the highest cooling loads. We have assumed the use of an "advanced technology" (high performance) collector and a water-glycol spray dessicant system. In all cases, the required collector areas are small in comparison to the available roof areas.

As illustrated in Figure 3.4.4 a central solar station can provide heat to the MIUS hot water distribution system or to drive a heat-actuated refrigeration machine (absorption chiller) which provides chilled water to the MIUS distribution network. In both instances collection must take place at high temperatures (near 170°F or above). Table 3.4.14 summarizes the potential economics of central solar thermal-energy collection. The non-specific application considered in Table 3.4.14 is based on the use of 50,000 ft^2 of advanced tracking collectors, which have a total system cost (including the tracking mechanism) of $\$15/ft^2$ (See Table 2.2.1). We also assumed average collection efficiencies for the summer and remaining months of the year. They are based on summertime energy collection at 210°F to drive the absorption chiller, and energy collection at around 170° - 180°F during the remaining year. For the cooling season, the solar system provides about 0.4×10^6 ton-hours of refrigeration, potentially displacing 280 MW-HR of electric vapor-compression cooling.* During the fall, winter and spring heating seasons the solar system provides about 20×10^9 BTU of heat. If we assume an amortization rate of 10% per year, and proportion the annual capital charges to the heating and cooling functions according to the fractions of the year these functions are performed, the equivalent cost of cooling is about 6.7¢/kwh of electrical energy displaced ($\$75,000 \times 0.25/280,000$ kwh), and about $\$2.80/10^6$ BTU of heat energy. These costs are comparable to the costs of conventional energy. However, they are based on the assumption of relatively inexpensive tracking collectors and the presumption that the heat displaced by the solar system in the fall, winter and spring seasons has economic value.

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* During the summer months there is insufficient high-temperature waste heat to meet the cooling load by absorption refrigeration.

TABLE 3.4.11

ADDITIONAL INDIVIDUAL UNIT APPLICATIONS

Building	Approximate Roof Area (ft^2)	Collector Area (ft^2)			Energy Savings/ Complex (10^6 BTU)		
		HW	HW/Heat	Cool	HW	HW/Heat	Cool
Garden Apt.	370	36	118	540	8749	28576	19926
Elementary school	20000	820	827	11600	610	621	1320
High School	30000	5436	6637	52700	1360	1660	2000
Mid School	25000	5436	6782	50400	1360	1697	1913
High Rise	13000	3369	4500	8350	5060	6750	1902
Commercial	50000	309	2381	53100	77	596	2014
Recreational	20000	736	1772	26150	184	443	993

1. HW and HW/Heat: 130° collection temp, selective surface, %S=60%, efficiency ≃ 45%
   Cool: 200°F collection temperature, advanced collector, %S = 50%, efficiency ≃ 35%, COP = 0.65

Table 3.4.12

APPLICATION HIGH SCHOOL - DEHUMIDIFICATION

ANNUAL LOAD 600 x 10^6 BTU

CONCEPT	TEMP. LEVEL	COLLECTOR TYPE	SIZE* (ft^2)	IMPACT ON MIUS	TECHNOLOGY STATUS	ECONOMIC CONSIDERATIONS
1. Water-glycol spray, COP = 0.5	150°F	Selective Surface	4,300	Reduce Annual Chilling Load by 300 x 10^6 BTU	Near Term	Reduce Electric Air Conditioning
2.	↓	Advanced	2,700	↓	In Development (2 - 4 years)	↓
3. Bed-type Dessicant, COP = 0.7	180°F	← same as Concepts 1 and 2 →				
4. Rotary Wheel COP = 0.7	250	Advanced	3,061	← same as Concepts 1-3 →		

*Base on meeting 50% of the load

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TABLE 3.4.13

COLLECTOR AREAS REQUIRED TO

PROVIDE 50% SOLAR DEHUMIDIFICATION *

Building	Roof Area (ft^2)	Latent Load (10^6 BTU)	Collector Area (ft^2)
High School	30,000	600	2,700
Mid-school	25,000	575	2,590
Recreation Area	20,000	300	1,350
Commercial	50,000	600	2,700

* Assume water-glycol spray, advanced collector

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TABLE 3.4.14

TYPICAL ECONOMICS OF

CENTRAL SOLAR THERMAL POWER COLLECTION

A. Concept — Supply high temperature (210°F) heat to drive existing absorption air conditioner during the summer months. Use collectors to supply heat during the remaining seasons of the year.

B. Technical Data

- Advanced (tracking) collectors @ $15/ft^2 system cost
- COP of A/C = 0.65
- Assume 50,000 ft^2 of collector area
- Summer average efficiency ≃ 0.50

  Fall, winter, spring average efficiency ≃ 0.65
- Summer solar flux ≃ $.27 \times 10^6$ BTU/ft^2

  Fall, winter, spring solar flux ≃ $.61 \times 10^6$ BTU/ft^2

C. Cooling/Heating Accomplished

1. Cooling

- Delivered: $50{,}000 \times 0.5 \times 0.27 \times 10^6 \times 0.65 / 12{,}000 = 0.37 \times 10^6$ ton-hrs
- Electricity saved: 280 MW - hrs

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CENTRAL COLLECTION ECONOMICS, (cont.)

2. Heating

- Delivered: $50{,}000 \times .65 \times .61 \times 10^6 = 19{,}800 \times 10^6$ BTU

D. Equivalent Cost

- Total system cost = $750,000
- Assume 10% amortization rate: $75,000/year
- Cooling energy (electricity) saved = 6.7¢ kwh
- Heating energy supplied = $2.84/$10^6$btu
- Reduction in size of electrical demand: 0.86%

3.5 Overall Assessment of Candidate Solar Concepts

An overall assessment was made of the identified MIUS candidate solar thermal energy concepts to determine those worthy of further study. As a first step, all the system costs were rated using the weighted system evaluation procedure described in Table 2.1.1, where the maximum possible overall score for any concept was 125. A summary of the overall numerical ratings is shown in Table 3.5.1, along with the details of the individual scores given to factors such as State of the Art, potential economics, type of energy reduction (electrical or thermal) and ease of integration. This display highlights the apparent strengths and weaknesses of the preliminary concepts.

As an aid to screening and selecting concepts for further evaluation, additional illustrations were prepared to display the following potential impacts that the systems concepts had on the Village Complex MIUS:

- Impact on total annual electrical energy requirements (Figure 3.5.1)
- Impact on total annual thermal energy requirements (Figure 3.5.2)
- Impact on land usage considering unstructured land, park land, and developed land in both the Village Center (Figure 3.5.3) and the Neighborhood (Figure 3.5.4) elements of the Village Complex.

The illustrations show that solar water heating, and combined water and space heating systems in the single-family detached residences (which achieved the highest ratings) can provide the equivalent of 15 to 30 MW-hr of energy to the Village Complex MIUS. Additionally, these systems have a negligible impact on land usage since all the solar collectors that are required can be installed on the available roof area. At the opposite extreme, the Wastewater Influent Temperature Stabilization Concept (which received the lowest overall rating) imposed an unacceptable demand on land use while providing only a minor reduction in fuel consumption.

The final summary of the overall evaluation of the candidate systems is presented in Table 3.5.2.

Within the Wastewater Management Subsystem, solar sludge drying and solar wastewater influent temperature stabilization ultimately were judged unattractive. The major reasons for the poor showings include: a) extensive area requirements where little suitable land is available, b) minor fuel savings, and c) unfavorable economics (large incremental capital investment charges per unit delivered thermal energy). It is worth indicating that the unfavorable judgments on the above solar concepts were made assuming these solar applications did not have to compete against essentially free MIUS waste heat. The availability of sufficient waste heat clearly obviates these two solar concepts.

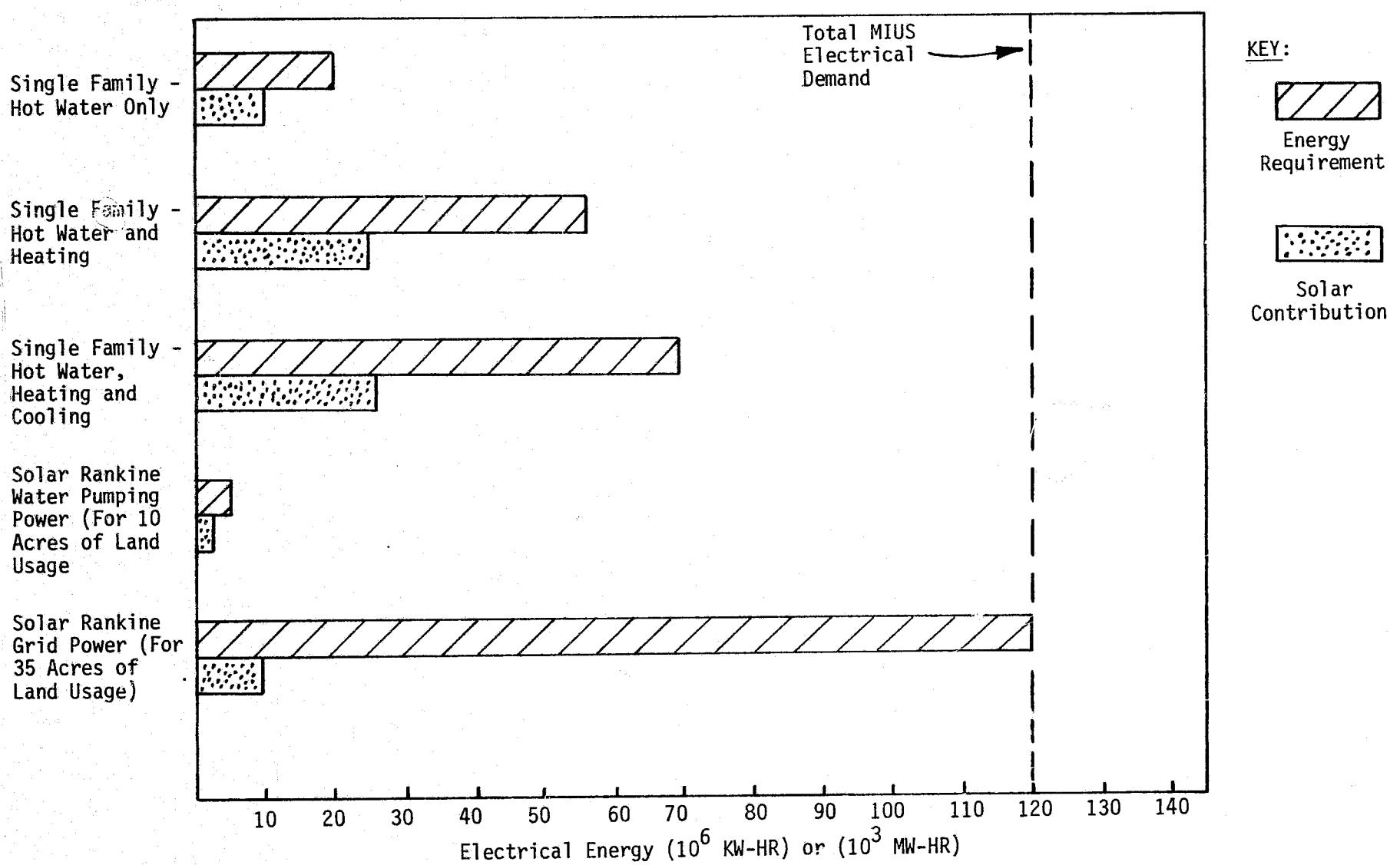


FIGURE 3.5.1

IMPACT OF SEVERAL SOLAR APPLICATIONS ON ANNUAL ELECTRICAL ENERGY REQUIREMENTS OF VILLAGE COMPLEX

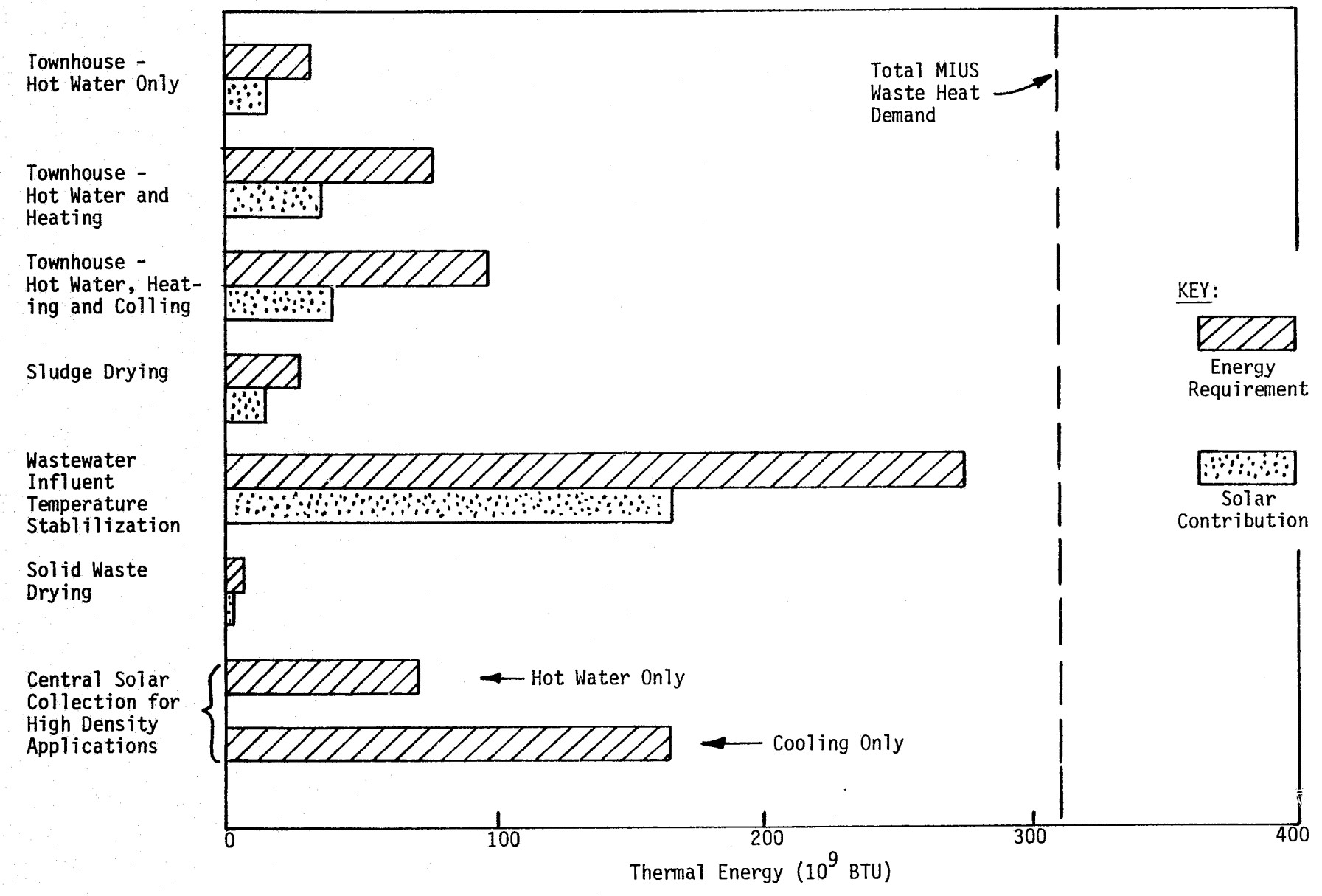
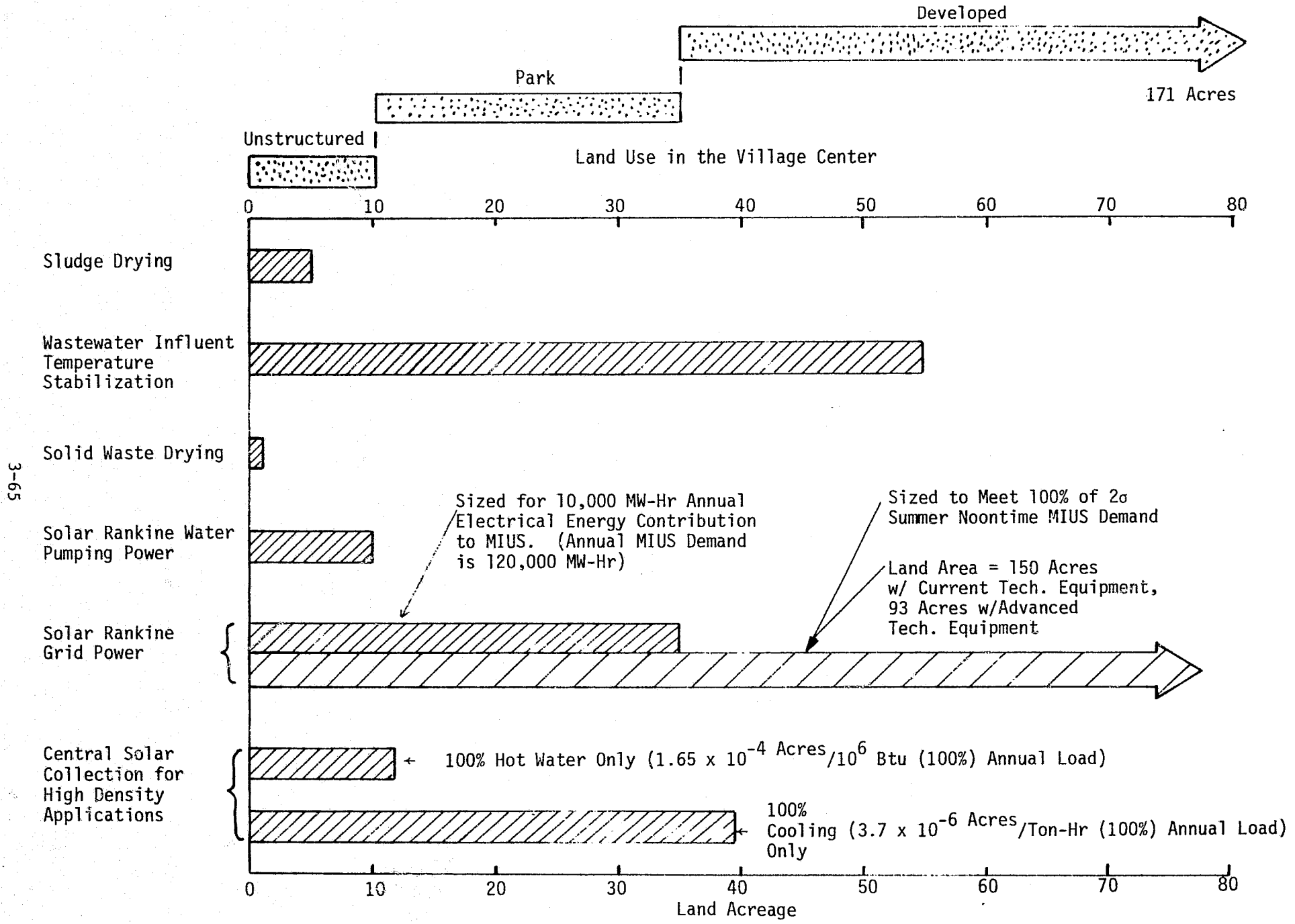


FIGURE 3.5.2 IMPACT OF SEVERAL SOLAR APPLICATIONS ON ANNUAL THERMAL ENERGY REQUIREMENTS OF VILLAGE COMPLEX

FIGURE 3.5.3 LAND AREA IMPACT ON THE VILLAGE CENTER



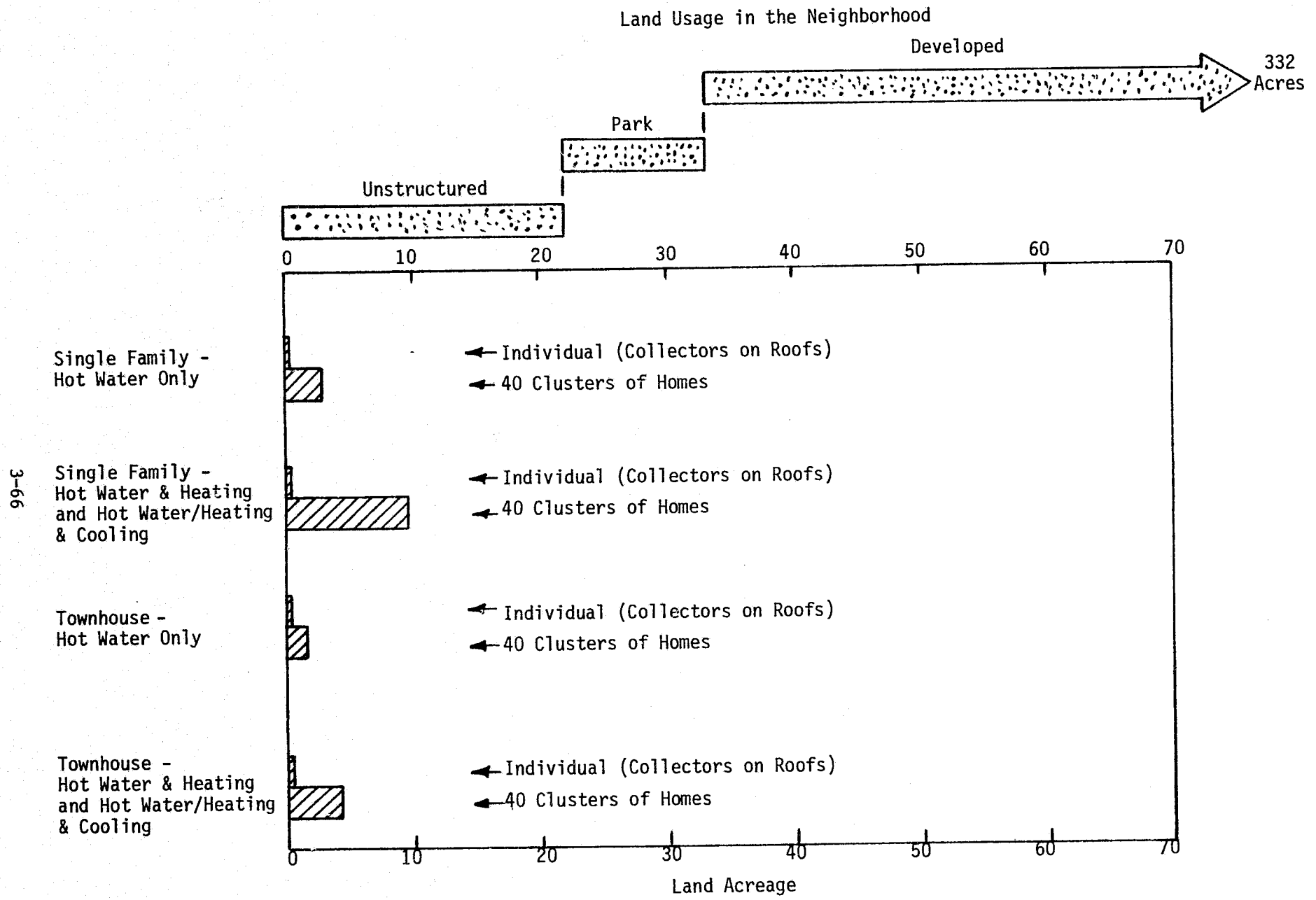


FIGURE 3.5.4 LAND AREA IMPACT ON THE NEIGHBORHOOD

TABLE 3.5.1

NUMERICAL RATING OF SOLAR THERMAL ENERGY CONCEPTS IN MIUS

CONCEPT	STATE OF THE ART	POTENTIAL ECONOMICS	ENERGY REDUCTION	EASE OF INTEGRATION	TOTAL SCORE
I. WASTEWATER MANAGEMENT SUBSYSTEM					
A. Sludge Drying	15	0	14	9	38
B. Waste Water Influent Temp. Stabilization	25	0	7	0	32
II. SOLID WASTE MANAGEMENT SUBSYSTEM					
A. Solid Waste Drying	15	0	14	9	38
III. POWER GENERATION SUBSYSTEM					
Rankine Cycle					
A. Solar-Rankine					
1. Water pumping Power	10	10	28	9	57
2. Grid Power Generation	10	10	35	9	64
B. Combined Solar and Waste Heat Grid Power Generation	10	20	35	9	74
IV. HVAC SUBSYSTEM					
A. Low Density Units-Single Family Detached Homes					
1. Individual Solar Collector System for Each Unit:					
a) Hot Water	25	50	35	15	125
b) Hot Water and Space Heating	25	40	35	15	115
c) Solar-Heat Pump	25	40	35	12	112
d) Combined Heating and Cooling	20	20	35	9	84

TABLE 3.5.1

NUMERICAL RATING OF SOLAR THERMAL ENERGY CONCEPTS IN MIUS (CONT'D.)

CONCEPT	STATE OF THE ART	POTENTIAL ECONOMICS	ENERGY REDUCTION	EASE OF INTEGRATION	TOTAL SCORE
IV. HVAC SUBSYSTEM, (cont.)					
2. Common Solar Collector System for Cluster of Units:					
a) Hot Water	20	30	35	9	94
b) Hot Water and Space Heating	20	20	35	9	84
c) Solar-Heat Pump	20	20	35	6	81
d) Combined Heating and Cooling	20	10	35	6	71
B. High Density Units					
1. Individual Solar Collector System for Each Unit:					
a) Hot Water	25	50	21	15	111
b) Hot Water and Space Heating	25	40	21	15	101
c) Combined Heating and Cooling	20	20	21	9	70
2. Common Solar Collector System for Cluster of Townhouses					
a) Hot Water	20	30	21	9	80
b) Hot Water and Space Heating	20	20	21	9	70
c) Combined Heating and Cooling	20	10	21	6	57
3. Centralized Collector System Integrated with HVAC Distribution Subsystem					
a) Hot Water	20	50	21	9	100
b) Hot Water and Space Heating	20	40	21	9	90
c) Combined Heating and Cooling	20	40	35	9	104

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TABLE 3.5.1

NUMERICAL RATING OF SOLAR THERMAL ENERGY CONCEPTS IN MIUS (CONT'D.)

CONCEPT	STATE OF THE ART	POTENTIAL ECONOMICS	ENERGY REDUCTION	EASE OF INTEGRATION	TOTAL SCORE
IV. HVAC SYBSYSTEM (cont.)					
4. Dehumidification					
a) Individual Solar Collector and Dehumidification Subsystems for Each Unit	20	20	35	9	84
b) Centralized Solar Collector and Dehumidification Subsystems	5	10	35	3	53

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Solar solid-waste (trash) drying was also found to be attractive for reasons similar to those outlined in the previous paragraph on the Wastewater Management Subsystem.

The screening of the solar power generation concepts revealed that pure solar grid-power and solar shaft pumping-power were unattractive because of large land acreage requirements, low annual energy impact on the MIUS, and poor economics. However, the preliminary evaluation of the hybrid solar and waste-heat bottoming power production scheme revealed the need for further detailed studies of the relative contributions of the solar power, waste-heat bottoming power and diesel prime-mover power. A need was also sensed for a clarification of the primary economic variables which establish the economic feasibility of the concept.

As indicated earlier, the HVAC Subsystem was arbitrarily divided into low-density unit applications (units tied into the MIUS piping network). The solar concepts which evolved for the low-density units included solar domestic hot-water production, solar hot-water and space heating and cooling. In addition, the above applications were considered for the low-density units taken individually and taken in small clusters. Primarily due to economics and MIUS energy impact, the preliminary evaluation and screening process resulted in favorable judgments for only solar domestic hot-water production and for solar hot water and space heating in the low-density units taken individually.

Within the high-density sector of the HVAC Subsystem, solar domestic hot-water production, solar hot water and space heating, and combined solar heating and cooling were considered for the townhouses (taken both individually and in small clusters) and for a centralized solar collector system integrated with the MIUS piping network. Because of the general availability of MIUS waste heat, most of the above concepts were found to be economically unattractive. However, because of the summertime waste heat deficiency and the substantial auxiliary vapor-compression air conditioning electrical load, promise was indicated for centralized combined heating and cooling. The preliminary evaluations and screenings of solar desiccant dehumidification in both low and high density units resulted in an unfavorable judgment for application of this concept in a centralized system or in residences - either single family detached homes or townhouses. These judgments are based primarily on poor economic showing and technical impracticalities. Solar dehumidification did appear promising, however, in individual high-density units in the Village Complex, such as schools and hospitals. It was concluded that the technology on desiccant systems has tended to be a very specific and application-oriented art which is now receiving increased attention in response to interest in solar energy and general energy conservation. Its status is analogous to that of absorption refrigeration technology before specific development activities were directed to solar energy applications.

In summary, the solar concepts which survived the preliminary screening and evaluation stage, and which were deemed worthy of a more detailed review, were:

- Combined Solar and Waste-Heat Bottoming Rankine-Cycle Engine Power Generation
- Solar Domestic Hot Water Production and Solar Hot Water and Space Heating in the Single-Family Detached Residences, including Heat Pump Utilization
- Central Combined Heating and Cooling for High-Density Units
- Solar Desiccant Dehumidification of Individual Buildings Connected to Central HVAC Subsystems

The basis of selecting the various applications for further study was to either present a more detailed evaluation of a clearly promising concept or to develop additional information to refine an estimate of a concept's potential and point out the primary variables impacting economic and technical feasibility.

TABLE 3.5.2

OVERALL EVALUATIONS OF PRELIMINARY SOLAR-APPLICATION CONCEPTS

CONCEPT	RATING SCORE	LAND USE REQUIREMENTS			POTENTIAL FOR REDUCING FUEL CONSUMPTION IN MIUS			OVERALL EVALUATION			COMMENTS
		Incompatible	Compatible	None	Minor	Moderate	Significant	Unattractive	Uncertain	Promising	
I. WASTEWATER MANAGEMENT SUBSYSTEM											
A. Sludge Drying	38		●		●			●			REQUIRES EXTENSIVE LAND AREA AND INCREASE IN CAPITAL INTESTMENT WITH MINOR REDUCTION IN FUEL CONSUMPTION.
B. Wastewater Influent Temperature Stabilization	32	●			●			●			REQUIRES UNAVAILABLE LAND AREA AND SUBSTANTIAL INCREASES IN CAPITAL INVESTMENT.
II. SOLID WASTE MANAGEMENT SUBSYSTEM											
A. Solid Waste Drying	38		●		●			●			REQUIRES SUBSTANTIAL CAPITAL INVESTMENT IN UNPROVEN EQUIPMENT AND TECHNOLOGY.
III. POWER GENERATION SUBSYSTEM											
A. Solar Rankine Cycle											
1. Water Pumping Power	57		●		●			●			FEASIBILITY DEPENDENT UPON PROGRESS IN DEVELOPMENT OF LOW-TEMPERATURE RANKINE ENGINES. COLLECTOR LAND AREA IMPACT ON CUMMUNITY LARGE IN PROPORTION TO IMPACT OF ANNUAL ENERGY CONTRIBUTION.
2. Grid Power Generation											
a) < 1 MW (PEAK POWER)	64		●		●			●			
b) 1-10 MW (PEAK POWER)	64	●	●			●		●		●	
c) > 10 MW (PEAK POWER)	64	●					●	●			

TABLE 3.5.2 (Continued)

CONCEPT	RATING SCORE	LAND USE REQUIREMENTS			POTENTIAL FOR REDUCING FUEL CONSUMPTION IN MIUS			OVERALL EVALUATION			COMMENTS
		Incompatible	Compatible	None	Minor	Moderate	Significant	Unattractive	Uncertain	Promising	
POWER GENERATION SUBSYSTEM, (Cont.)											
B. Combined Solar and Waste Heat Rankine Cycle Engine Power Generation											
1. Solar Contribution:											
a) < 1 MW (PEAK POWER)	74		●		●			●			IMPROVES EFFICIENCY AND REDUCES SIZE OR PRIME MOVER. PRODUCES HEAT DEFICIENCY WHICH CAN BE MADE UP AND EXCEEDED BY APPLICATION OF SOLAR ENERGY.
b) 1-10 MW (PEAK POWER)	74	●	●			●	●			●	
c) >10 MW (PEAK POWER)	74	●					●	●			
IV. HVAC SUBSYSTEM											
A. Low Density Units-Single Family Detached Homes											SOLAR ENERGY DISPLACES ELECTRICITY, NOT WASTE HEAT USAGE.
1. Individual Solar Collector System for Each Unit:											
a) Hot Water	125			●			●			●	
b) Hot Water and Space Heating	115			●			●			●	
c) Solar-Heat Pump	112			●			●			●	
d) Combined Heating and Cooling	84			●			●	●			OVERALL EVALUATION OF COMBINED HEATING AND COOLING BASED ON EMPLOYMENT OF ABSORPTION AIR CONDITIONING UNIT. ECONOMICS UNATTRACTIVE IN THE NEAR TERM.

TABLE 3.5.2 (Continued)

CONCEPT	RATING SCORE	LAND USE REQUIREMENTS			POTENTIAL FOR REDUCING FUEL CONSUMPTION IN MIUS			OVERALL EVALUATION			COMMENTS
		Incompatible	Compatible	None	Minor	Moderate	Significant	Unattractive	Uncertain	Promising	
IV. HVAC SUBSYSTEM, (cont.)											
2. Common Solar Collector System for Cluster of Units:											
a) Hot Water	94	●					●	●			
b) Hot Water and Space Heating	84	●					●	●			UNDEVELOPED LAND UNSUITABLE FOR APPLICATION OF CLUSTERED COLLECTORS.
c) Solar Heat Pump	81	●					●	●			
d) Combined Heating and Cooling	71	●					●	●			
B. High Density Units											
1. Individual Solar Collector System for Each Unit:											
a) Hot Water	111			●	●			●			
b) Hot Water and Space Heating	101			●	●			●			DISPLACES USE OF WASTE HEAT. ATTRACTIVE ONLY IN SITUATIONS WITH LARGE HEAT DEFICIENCY.
c) Combined Heating and Cooling	70			●		●		●			

TABLE 3.5.2 (Continued)

CONCEPT	RATING SCORE	LAND USE REQUIREMENTS			POTENTIAL FOR REDUCING FUEL CONSUMPTION IN MIUS			OVERALL EVALUATION			COMMENTS
		Incompatible	Compatible	None	Minor	Moderate	Significant	Unattractive	Uncertain	Promising	
IV. HVAC SUBSYSTEM, (cont.)											
B. High Density Units											
2. Common Solar Collector System for Cluster of Townhouses											
a) Hot Water	80	●			●			●			
b) Hot Water and Space Heating	70	●			●			●			UNDEVELOPED LAND UNSUITABLE FOR APPLICATION OF CLUSTERED COLLECTORS.
c) Combined Heating and Cooling	57	●				●		●			
3. Centralized Collector System Integrated with HVAC Distribution System:											
a) Hot Water	100		●		●			●			← DISPLACES USE OF WASTE HEAT. ATTRACTIVE ONLY IN SITUATIONS WITH LARGE HEAT DEFICIENCY.
b) Hot Water and Space Heating	90		●		●			●			←
c) Combined Heating and Cooling	104		●			●				●	← POTENTIAL FOR DISPLACING AUXILIARY VAPOR-COMPRESSION AIR CONDITIONING.

TABLE 3.5.2 (Continued)

CONCEPT	RATING SCORE	LAND USE REQUIREMENTS			POTENTIAL FOR REDUCING FUEL CONSUMPTION IN MIUS			OVERALL EVALUATION			COMMENTS
		Incompatible	Compatible	None	Minor	Moderate	Significant	Unattractive	Uncertain	Promising	
IV. HVAC SUBSYSTEM, (cont.)											
B. High Density Units											
4. Dehumidification											
a) Individual Solar Collector and Dehumidification Subsystems for Each Unit	84			●		●			●—●		POTENTIAL FOR DISPLACING AUXILIARY VAPOR-COMPRESSION AIR CONDITIONING.
b) Centralized Solar Collector and Dehumidification Subsystems	53		●			●		●			REQUIRES IMPRACTICAL AIR OR DESSICANT DISTRIBUTION SYSTEM.

4.0 EXTENDED EVALUATION OF SELECTED SOLAR CONCEPTS

4.1 Combined Solar and Waste-Heat Bottoming Rankine-Cycle Engine Power Generation

Our preliminary screening analysis of several solar power-generation concepts has revealed a number of interesting technical and economic features associated with the hybrid solar and waste-heat bottoming power generation scheme. Most of these features center around the significant contributions to the Village Compex's electrical power needs resulting in large savings in fuel consumption. Furthermore, the dual utilization of the Rankine-cycle heat engine makes this energy savings possible with a minimum of redundance in power generation equipment. Figure 4.1.1 is useful in this regard for pointing out the potential savings in system complexity and capital costs associated with the sharing of heat engine components. As may be seen, only one heat engine, gear box, electrical generator, power transmission network, and switching and control subsystem are required with this dual energy-source concept. Of course, extra controls will be required to interface the separate contributions from the Rankine-cycle engine and diesel prime movers since these outputs are dependent on the sun's transient energy input and the trash burning schedule in the solid waste incineration facility.

4.1.1 Partitioning of Energy Generation

An important ingredient in the detailed performance analysis of the hybrid power-generation concept is the power and annual delivered energy partitions between the several power generation sources. A precise determination of these partitions demands a computer study of the Village Complex's time-varying operations, including climatological data input. Since such an analysis is beyond the scope of the present feasibility study, the energy partitioning analysis will necessarily be only approximate.

An analysis is presented in Appendix A.1 giving an expression for the diesel prime movers' fraction of the total MIUS electrical energy load. This expression was evaluated using the thermal efficiency of the MIUS prime mover and a Rankine-cycle engine efficiency found from the computer performance optimization study to be discussed in the next section. The results of the partitioning analysis for advanced and current technology equipment are given in Figure 4.1.2.

It is to be noted that in this analysis the waste-heat addition to the bottoming-cycle engine comes only from reject heat from the diesel prime-mover; incineration waste heat is neglected due to the complexity of its availability. Also not considered are the implications of the loss of waste heat suffered by the other MIUS functions, such as spacing conditioning applications. The energy output of the solar and waste-heat engine plus the prime mover output equals the total MIUS electrical load.

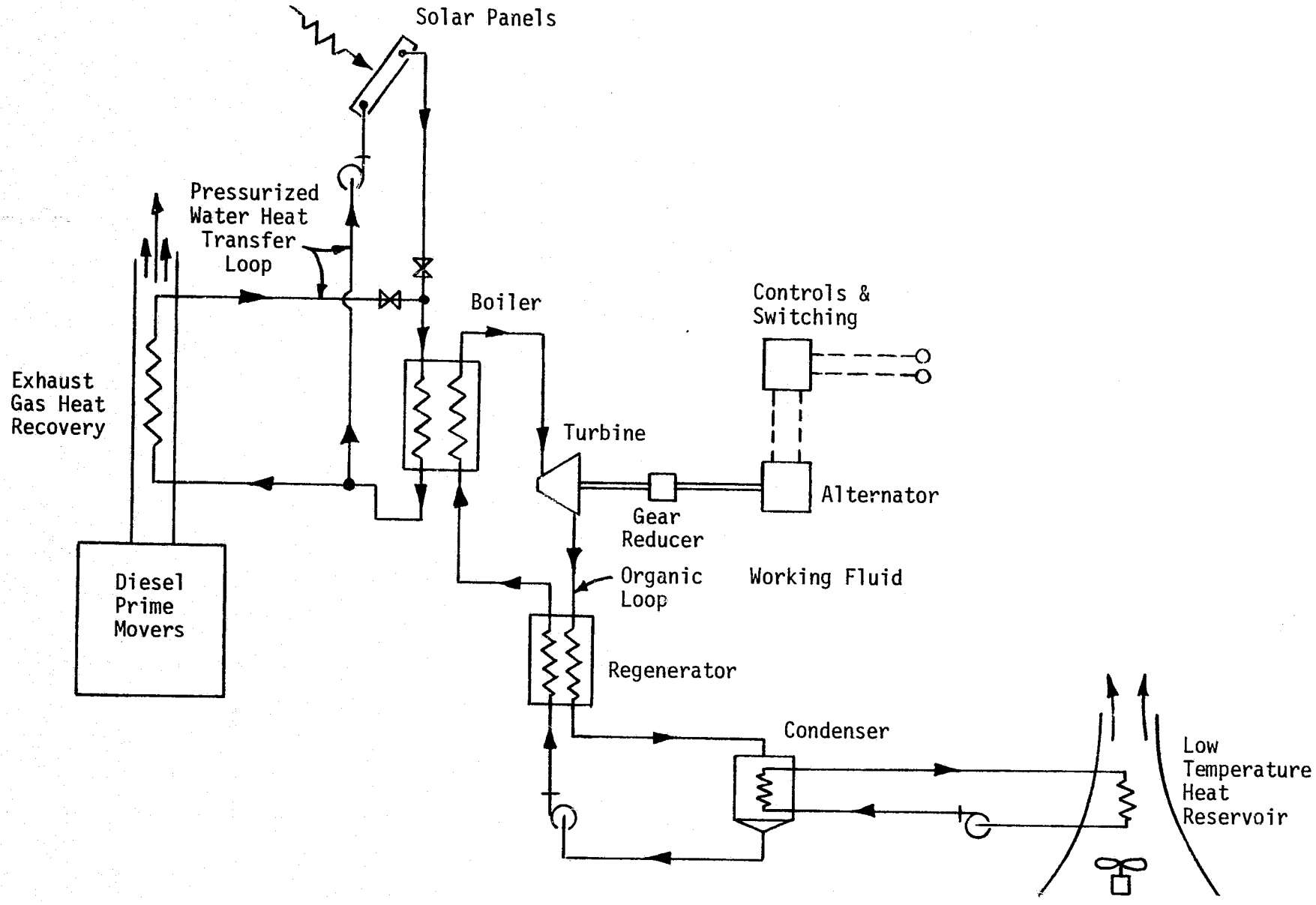


FIGURE 4.1.1

ARRANGEMENT OF SOLAR AND WASTE-HEAT BOTTOMING RANKINE-CYCLE POWER SYSTEM

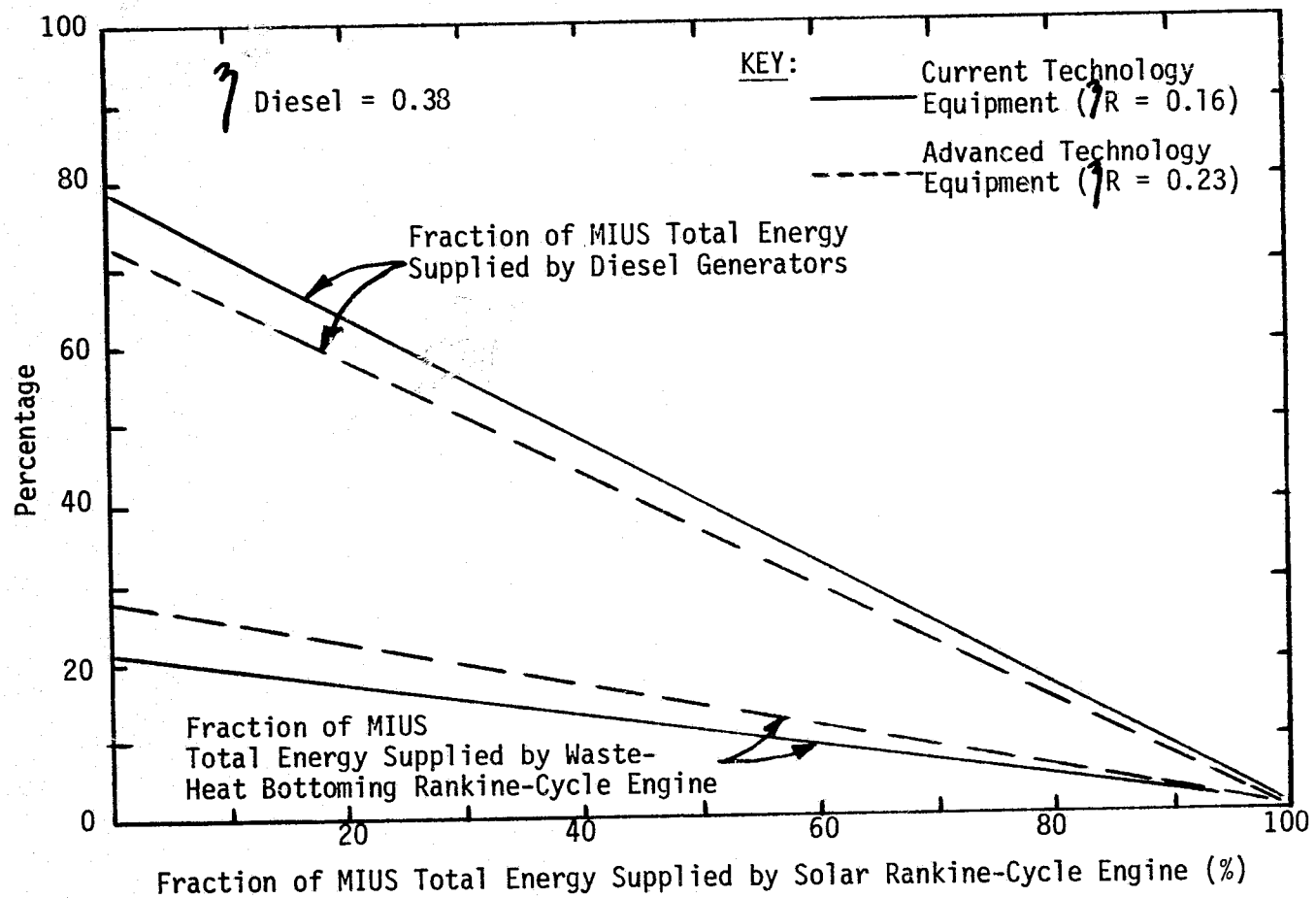


FIGURE 4.1.2

INFLUENCE OF THE SOLAR CONTRIBUTION OF SOLAR AND WASTE-HEAT BOTTOMING RANKINE-CYCLE ENGINE

At zero solar contribution to the total MIUS electrical load, a 28% reduction in diesel prime-mover energy output (and fuel input) is produced by using advanced technology equipment. This decrease in output is, of course, picked up by the waste-heat bottoming portion of the Rankine-cycle engine. For current technology equipment with no solar contribution, the prime-mover reduction is about 21%.

As Figure 4.1.2 shows, a rapid reduction in required prime-mover energy is produced with increases in solar production of energy; the bottoming waste-heat power diminishes at a less rapid rate. At 10% solar contribution for advanced technology equipment, the diesel prime-mover output has been reduced 35%, while the bottoming waste-heat contribution to the total load is about 25%.

4.1.2 Energy, Power, and Land Area Impact

The next important aspect in the detailed analysis of hybrid power generation is the determination of land area requirements for stipulated solar energy contributions to the MIUS electrical load. Estimates of these requirements were obtained by exercising a computer program written for a similar solar power-generation situation. Typical monthly output from this study are given in Table A.2.1 in Appendix A.2.

Parameters characteristic of advanced and current technology equipment, plus climatological data for various locations in the United States were inputed into the program. The computer output included computed variables such as solar collector efficiency, heat engine efficiency, and overall system efficiency, to name only a few. These variables were examined as a function of collector panel temperature (in the manner indicated earlier in Figure 3.3.7) to determine the optimum system operating condition. This analysis is shown in Figure 4.1.3 for one of the situations studied. As can be seen, for advanced technology equipment utilized in the Washington, D.C. area, the optimum system efficiency occurs at about 350°F. For current technology equipment at the same location, the optimum temperature of operation was 250°F.

Figures 4.1.4 and 4.1.5 present monthly and daily delivered energy and power output for the conditions specified in Figure 4.1.3 and a solar panel temperature of the optimum condition. Figure 4.1.4 shows that because of climatological conditions, March and December represent the months of maximum and minimum energy production.

Based on computational results characterized by Figures 4.1.3 to 4.1.5, land area impact predictions were made for several locations in the United States, and these results are presented in Figures 4.1.6 and 4.1.7. The top illustrations give the land acreage required for a specified delivered energy contribution, whereas the lower figure gives the peak power production. Samples of the support data for these figures is presented in Tables A.2.2 and A.2.3 in Appendix A. As expected, current technology equipment required larger land areas than advanced technology equipment, given the same energy or power requirements. In

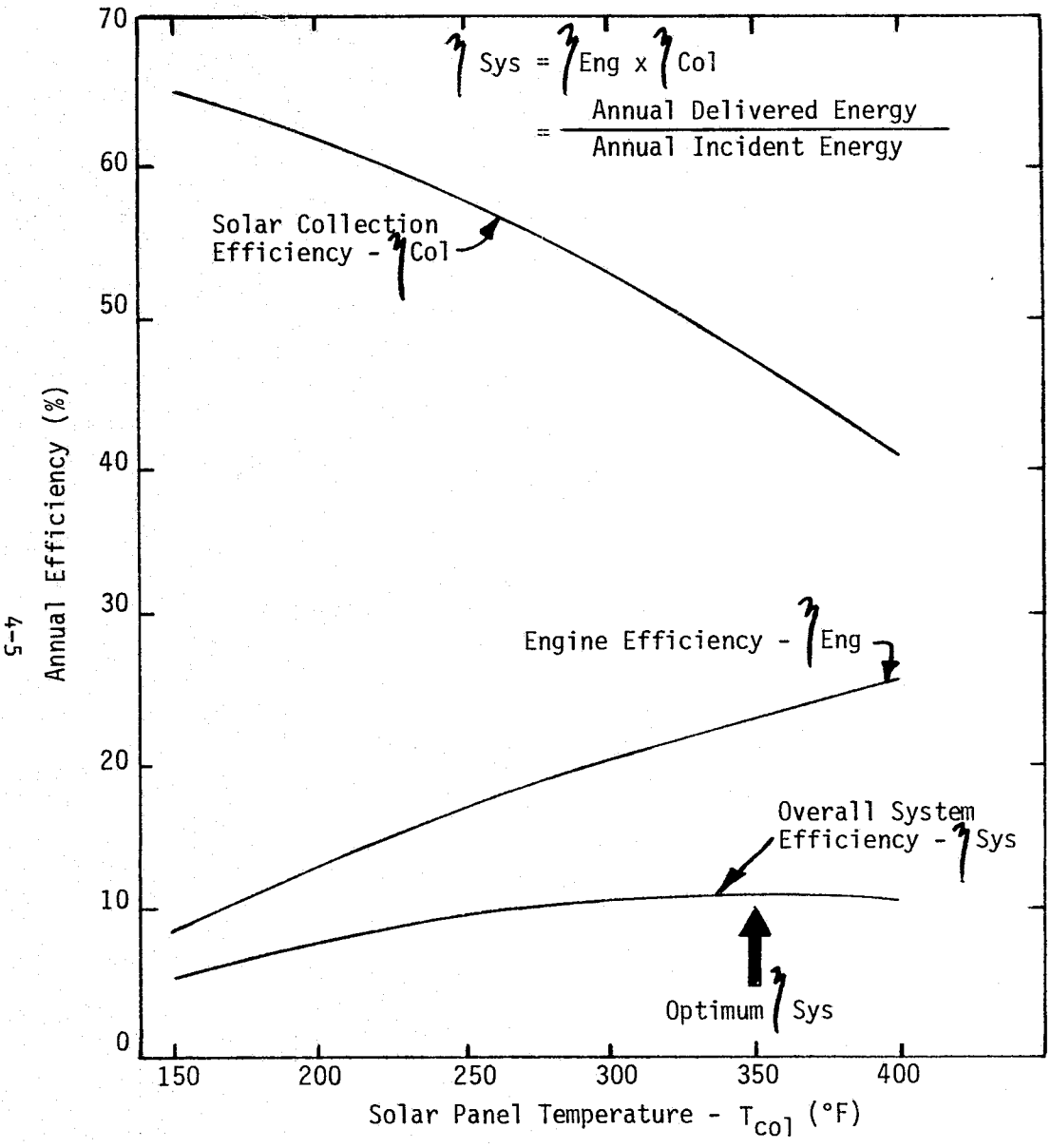


FIGURE 4.1.3

INFLUENCE OF SOLAR PANEL TEMPERATURE ON COMPONENT EFFICIENCIES IN SOLAR RANKINE-CYCLE ENGINE USING ADVANCED TECHNOLOGY EQUIPMENT IN WASHINGTON, D.C. AREA

Solar Panel Parameters

1. Collector Absorptivity = 0.93
2. Collector Emissivity = 0.08
3. Glass Absorptivity = 0.01
4. Glass Emissivity = 0.85
5. High Vacuum
6. Tilt Angle Fixed at = 38.6°
7. Heat Loss Coefficient = 0.05 Btu/Hour-Feet^2-°F
8. Anti-Reflection Glass Coating--Effective Index of Refraction = 1.35
9. Single Pane Cover Plate

Heat Engine Parameters

1. $\eta_{Eng} = 0.68 \eta_{Carnot}$
2. $\eta_{Carnot} = 1 - \frac{T_{rejection} + 460}{T_{addition} + 460}$
3. $T_{rejection}$ = Ambient Wet Bulb Temperature + 10°F
4. $T_{addition} = T_{col} - 10°F$

Climatic and Geographic Parameters

1. Latitude = 38.6°N
2. Monthly Mean Ambient Wet and Dry Bulb Temperatures, Wind Speed, and Percentage Available Sunshine Taken from "Climatic Atlas of the U.S.," GSA Envir. Data Service, June, 1968.

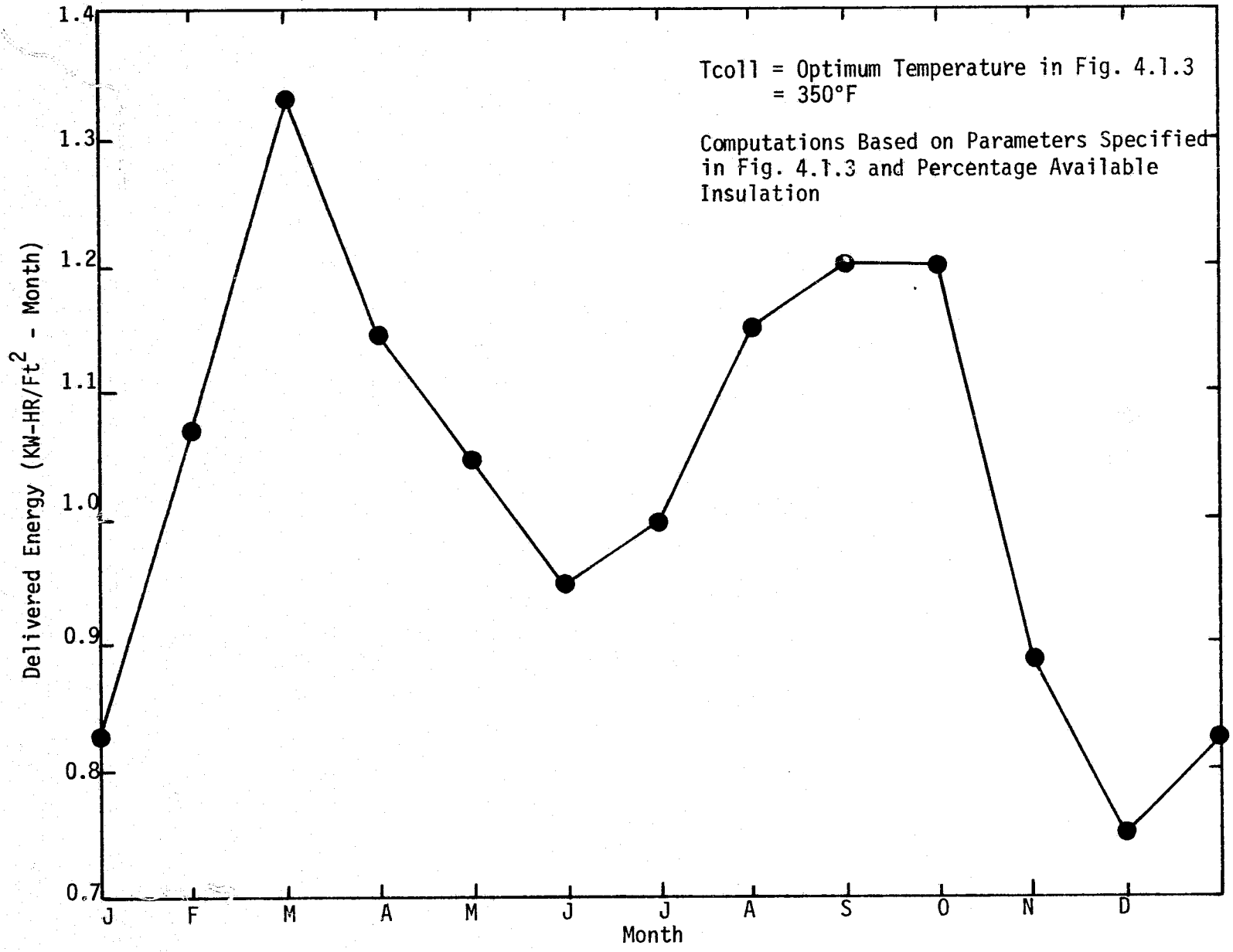


FIGURE 4.1.4

MONTHLY VARIATION OF DELIVERED ENERGY BY SOLAR RANKINE-CYCLE ENGINE

USING ADVANCED TECHNOLOGY EQUIPMENT IN WASHINGTON, D.C. AREA

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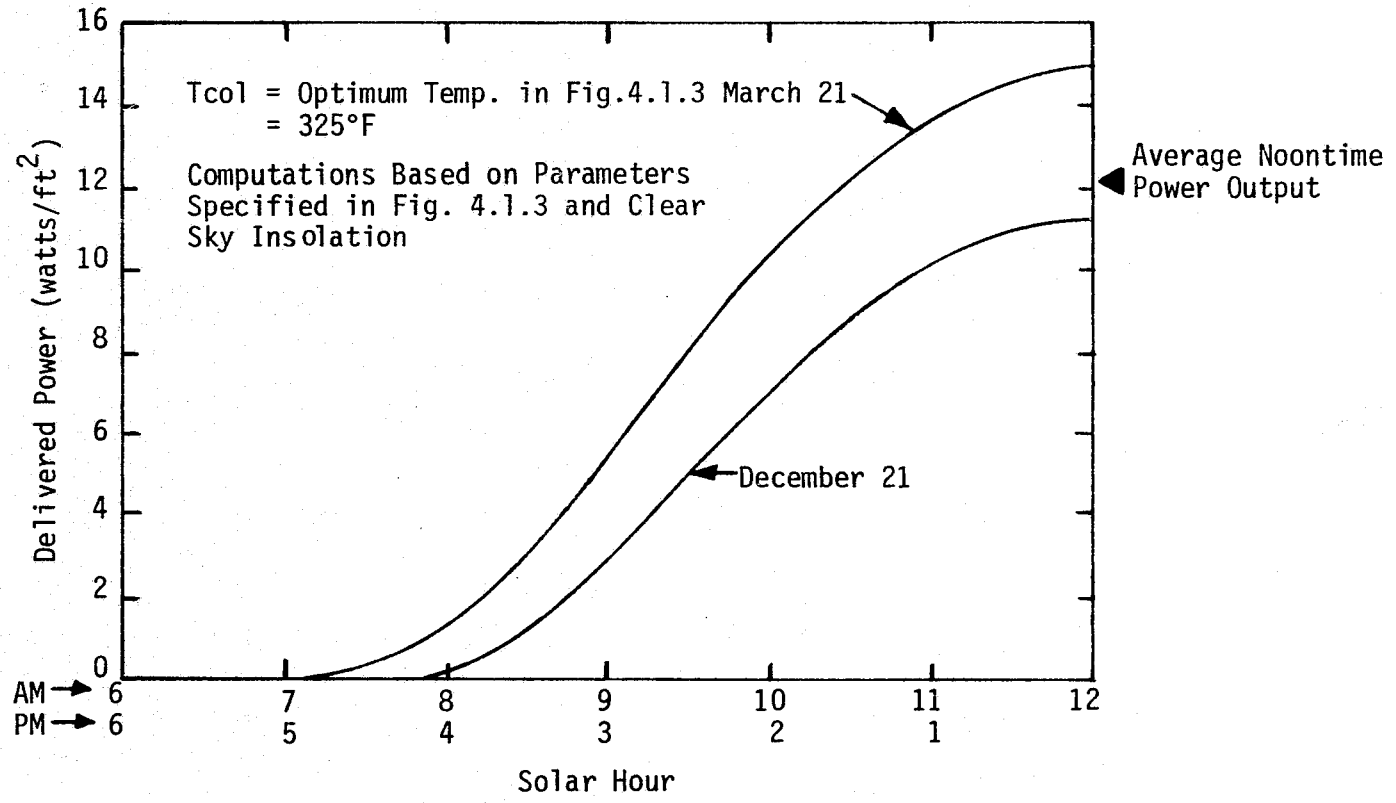
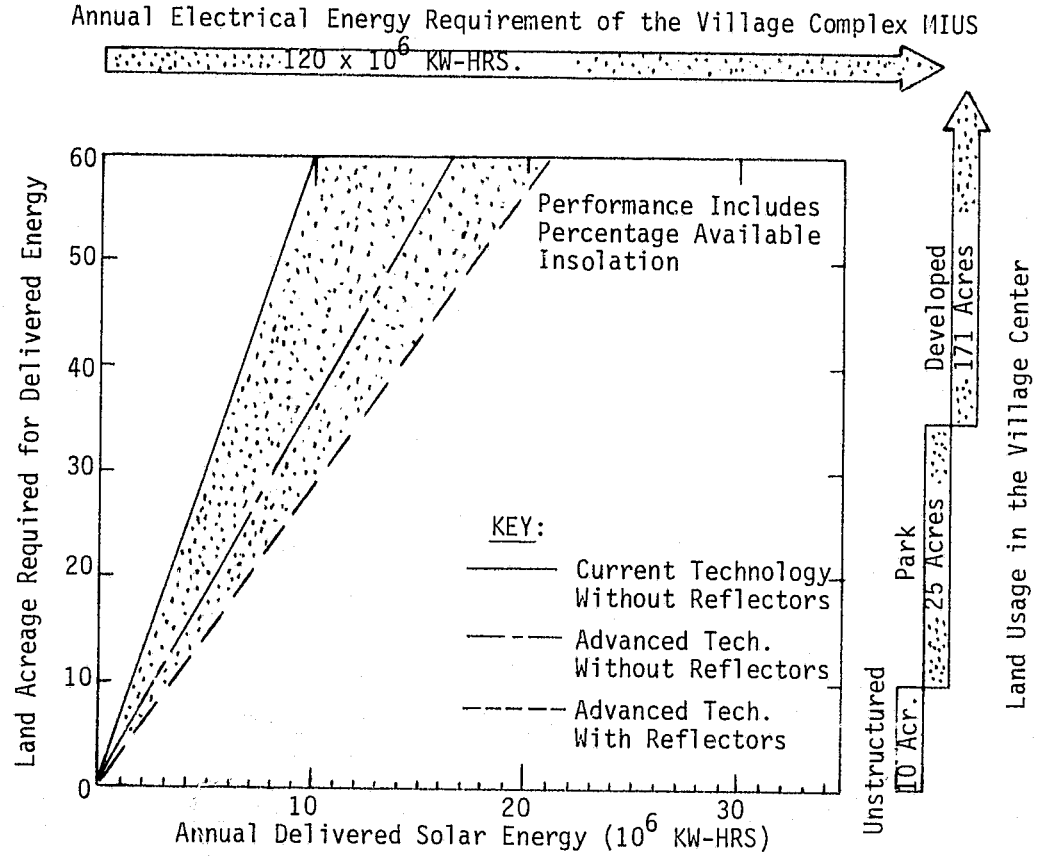
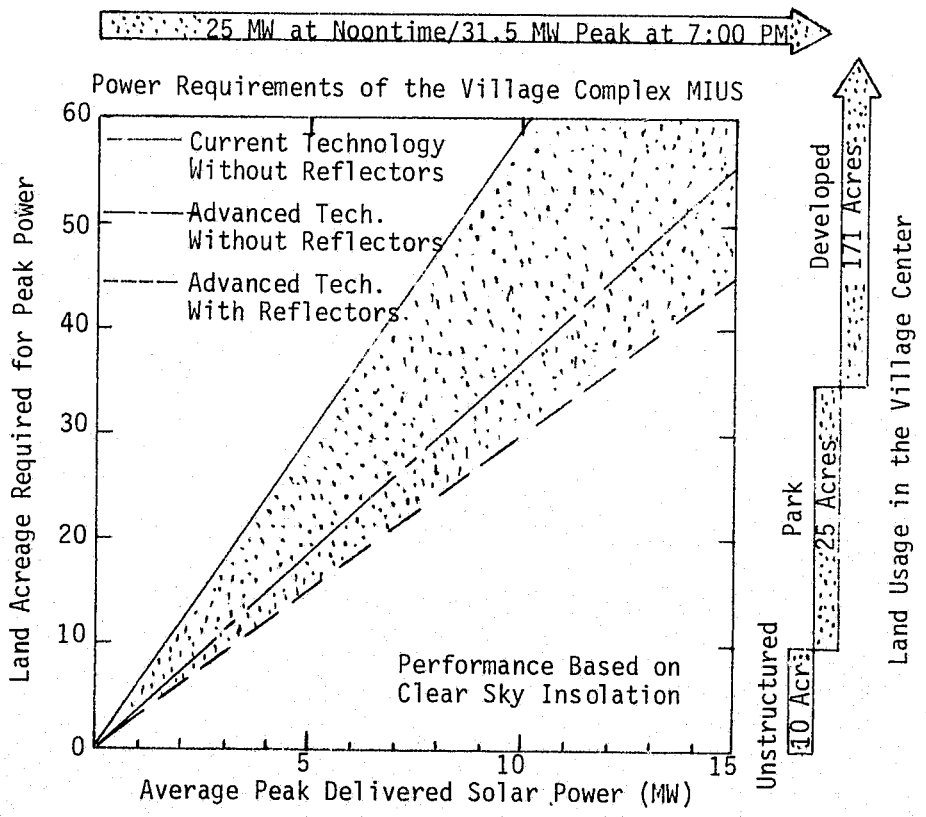


FIGURE 4.1.5

HOURLY VARIATION OF DELIVERED POWER BY SOLAR RANKINE-CYCLE ENGINE USING ADVANCED TECHNOLOGY EQUIPMENT IN WASHINGTON, D.C. AREA



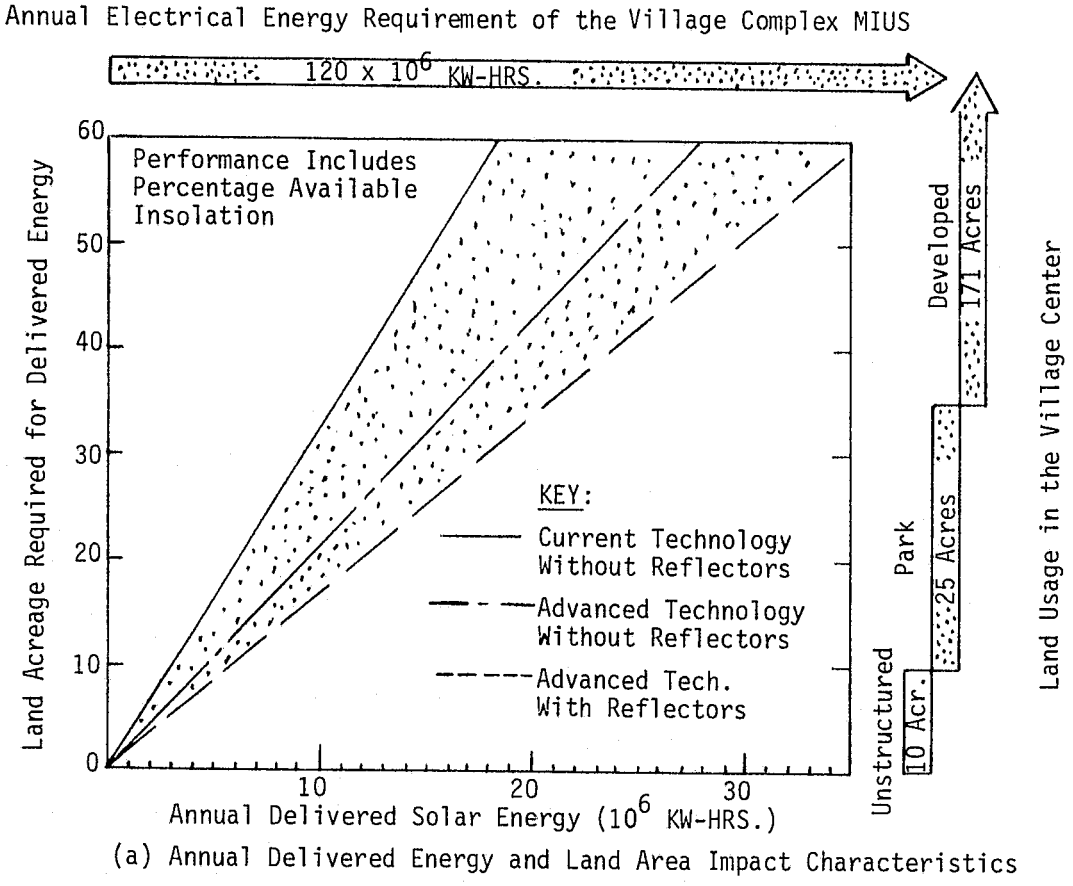
(a) Annual Delivered Energy and Land Area Impact Characteristics



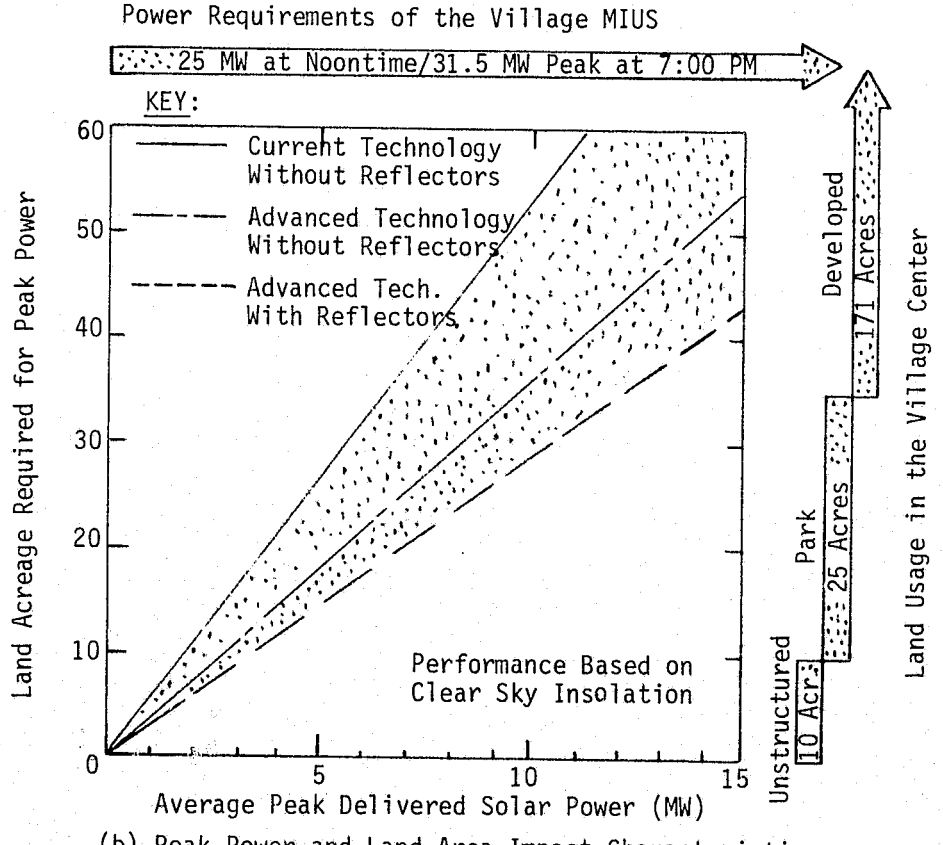
(b) Peak-Power and Land Area Impact Characteristics

FIGURE 4.1.6

SOLAR RANKINE-CYCLE ENGINE PERFORMANCE IN WASHINGTON, D.C. AREA



(a) Annual Delivered Energy and Land Area Impact Characteristics



(b) Peak Power and Land Area Impact Characteristics

FIGURE 4.1.7

SOLAR RANKINE-CYCLE ENGINE PERFORMANCE IN YUMA, ARIZONA AREA

addition, the extremely sunny Yuma, Arizona area requires significantly less collector area than the cloudier Washington, D.C. area, given the same annual delivered energy needs. It is interesting to note that the ratio of annual energy output to peak delivered power is independent of the status of the equipment technology, but, of course, depends on climatological conditions. For Washington, D.C., this ratio is about 1000 MW-HRS/PEAK MW, while for Yuma, Arizona, the ratio is approximately 1700 MW-HRS/PEAK MW. This result is primarily due to the difference in annual percentage available sunshine in the two locations (the annual incident solar flux in Washington, D.C. is about 0.56×10^6 BTU/Ft^2, whereas Yuma, Arizona has a value of 0.83×10^6 BTU/Ft^2).

Another useful feature of Figures 4.1.6 and 4.1.7 is the comparisons of land required to land available in the Village Center for various solar energy contributions to the MIUS electrical load. Using all the undeveloped plus park land of the Village Center (35 acres), an advanced technology solar power-system located in Washington, D.C. using fixed specular reflectors, would produce approximately a 10% contribution to the MIUS electrical load. (These reflectors are fixed, flat focusing devices that extend from the top back of one solar collector panel to the bottom of the panels in the next row. Their function is to enhance the solar flux incident on the collector panel surface.) For the Yuma, Arizona area, the same land area investment would yield an annual energy contribution close to 18% of the MIUS load.

4.1.3 Combined Solar and Waste-Heat Engine Performance and Land Area Requirements

Table 4.1.1 presents a summary of the results of the analyses discussed in the previous two sections for two locations in the United States. The first three columns give the annual partition between solar, waste-heat bottoming, and prime mover delivered energy. The next column presents the land area required for the stipulated solar contribution, while the fifth column shows the peak noontime solar power based on this land area. The last column gives the fractional solar contribution to the noontime MIUS power needs (about 25 MW) based on the area in column four. This last ratio can be used in Figure 4.1.2 to determine the waste-heat bottoming power generation and the diesel power generation, assuming the same proportionality holds as exists on an annual basis. From this later result, it is possible to size and price the Rankine-cycle and solar collection system, as discussed in the next section.

4.1.4 Economics of Combined Solar and Waste-Heat Bottoming Power Generation

In our preliminary examination of the costs of the solar and waste-heat bottoming power generation concept in Chapter 3, we saw that the unit energy cost of the solar portion of the scheme was significantly higher than the waste-heat bottoming cost. The purpose of the present section is to refine and sharpen those preliminary estimates, and to point out the primary economic variables which bear on the economic

TABLE 4.1.1

COMBINED SOLAR AND WASTE HEAT POWER GENERATION
CASE STUDY RESULTS

	Solar Fraction of MIUS Load $\frac{W_{R_S}}{W_M}$	Waste-Heat Bottoming Fraction of MIUS Load $\frac{W_{R_B}}{W_M}$	Diesel Fraction of MIUS Load $\frac{W_D}{W_M}$	Land Area Required A_{LAND} (ACRES)	Avg. Peak Solar Power $\frac{\dot{W}_{R_S}}{(MW)_{PK}}$	Avg. Solar Fraction of Noon-Time MIUS Load $\frac{\dot{W}_{R_S}}{\dot{W}_{M_{Noon}}}$
I. WASHINGTON, D.C.						
A. Advanced Tech. Equip. w/Reflectors:	0	0.28	0.72	0	0	0
	0.05	0.26	0.69	17	5.7	0.23
	0.10	0.25	0.65	34	11.3	0.46
	0.15	0.23	0.62	51	17.0	0.68
	0.20	0.22	0.58	68	22.7	0.91
B. Current Tech. Equip. wo/Reflectors:	0	0.21	0.79	0	0	0
	0.05	0.20	0.75	35.3	6	0.24
	0.10	0.19	0.71	70.6	12	0.48
	0.15	0.18	0.67	105.9	18	0.72
	0.20	0.17	0.63	141.2	24	0.96
II. YUMA, ARIZONA						
A. Advanced Tech. Equip. w/Reflectors:	0	0.28	0.72	0	0	0
	0.05	0.26	0.69	10.1	3.5	0.14
	0.10	0.25	0.65	20.2	7.0	0.28
	0.15	0.23	0.62	30.3	10.4	0.42
	0.20	0.22	0.58	40.4	13.9	0.56
B. Current Tech. Equip. wo/Reflectors:	0	0.21	0.79	0	0	0
	0.05	0.20	0.75	19.8	3.7	0.15
	0.10	0.19	0.71	39.6	7.3	0.29
	0.15	0.18	0.67	59.4	11.0	0.44
	0.20	0.17	0.63	79.2	14.7	0.59

feasibility of the hybrid power-generation concept. Table 4.1.2 displays a summarized cost breakdown of combined solar and waste-heat bottoming power generation. The bases for calculated results presented in the table can be found in Table A.3.1 in Appendix A. The equipment considered in the analysis was of an advanced technology nature, while the climatological conditions influencing the equipment size requirements corresponded to the Washington, D.C. area.

It may be seen in subsection A of Table 4.1.2 that the single largest capital expense in the hybrid power-generation concept is the cost of the solar collection system (4.85 million dollars), or nearly twice the cost of the dual-purpose heat engine (2.75 million dollars). When all of these costs are summed and compared to the number of units of energy generation, we find the unit cost of power generation for the hybrid system to be about 3.7¢/KW-HR.

It is informative to separate out the solar contribution from the waste-heat contribution and examine the unit costs of energy from each contribution. This has been done in subsections B and C in Table 4.1.2.

As shown, the unit cost of solar generated energy (16.8¢/KW-HR) is almost 14 times greater than the unit cost of waste-heat bottoming energy (1.2¢/KW-HR). It is, in fact, the very low cost of waste-heat bottoming energy which made possible the reasonable 3.7¢/KW-HR unit cost of energy for combined solar plus waste-heat energy generation.

The same type economic analysis as presented in Table 4.1.2 was performed for current technology equipment. Again, the Washington, D.C. area was the location of the study, and the solar contribution to the MIUS electrical load was arbitrarily selected to be 5%. The unit costs of energy are as follows: combined solar and waste-heat bottoming energy = 5.2¢/KW-HR; solar energy alone = 20.5¢/KW-HR; and waste-heat bottoming energy alone = 1.3¢/KW-HR.

We should note again that the 3.7¢/KW-HR unit energy cost for hybrid power from advanced technology equipment, and 5.2¢/KW-HR unit energy cost from current technology equipment are based on a 5% annual energy contribution from the solar portion of the Rankine-cycle engine. As the solar contribution is increased, the unit cost of hybrid energy shall also increase since, as seen in Figure 4.1.2, the lower-cost energy from the waste-heat bottoming part of the engine decreases in proportion.

From Figure 4.1.6 or Table 4.1.1, we again call attention to the land area requirements for a 5% solar energy contribution. These areas range from 17 to about 35 acres, which are substantial percentages of the available land in the Village Center. We have placed no monetary value on the use of this land, but the aesthetic value of land not covered with vast arrays of solar panels may be much higher than dollar value.

TABLE 4.1.2

ECONOMICS OF COMBINED SOLAR AND WASTE-HEAT BOTTOMING RANKINE-CYCLE ENGINE POWER GENERATION
(See Appendix A For Detailed Unit Costs)

Conditions:

- 5% solar contribution to MIUS electrical load.
- Advanced technology equipment.
- Washington, D.C. weather conditions.

A. Combined Solar and Waste-Heat Energy Costs

- Total capital charges
  - Solar collection subsystem = 4.85×10^6
  - Rankine-cycle engine = 2.75×10^6
  - Cooling tower = 0.37×10^6
  - Initial installed cost $\simeq$ 8.00×10^6
- Annual capital charge* (at 15%[8] of initial installed cost) = 1.20×10^6
- Annual electrical energy generation = 37.2×10^6 kw-hrs
- Fixed cost of electricity = $\$1.2 \times 10^6 / 37.2 \times 10^6$ kw-hrs = 3.2¢/kw-hr
- Operating cost+ = 0.5¢/kw-hr[9]
- Cost of producing hybrid solar and waste-heat electricity = 3.7¢/kw-hr

B. Solar Energy Costs

- Total capital charges
  - Solar collection subsystem = 4.85×10^6

* Includes: Cost of Capital, equity, indebtedness, depreciation, and taxes.
\+ Includes: Maintenance and overhaul, salaries for operating and supervisory personnel, general and administrative expenses, insurance, lubricants, additives, and miscellaneous expenses.

- Rankine-cycle engine = (5.7 mw/11 mw) x ($2.75 x 10^6) = 1.42×10^6
- Cooling tower = (5.7 mw/11 mw) x ($0.37 x 10^6) = 0.19×10^6
- Initial installed cost $\approx$ $\$6.50 \times 10^6$

- Annual capital charge (@ 15%) = $\$0.98 \times 10^6$
- Annual energy generation = 6×10^6 kw-hrs
- Fixed cost of electricity = $\$0.98 \times 10^6 / 6 \times 10^6$ kw-hrs = 16.3¢/kw-hr
- Operating cost = 0.5¢/kw-hr
- Cost of producing solar electricity $\approx$ 16.8¢/kw-hr

C. Waste-Heat Energy Costs

- Total capital charges
  - Rankine-cycle engine = (5.3 mw/11 mw) x ($2.75 x 10^6) = $\$1.32 \times 10^6$
  - Cooling tower = (5.3 mw/11 mw) x ($0.37 x 10^6) = 0.18×10^6
  - Initial installed cost $\approx$ $\$1.50 \times 10^6$
- Annual capital charge (@ 15%) = $\$0.23 \times 10^6$
- Annual energy generation = 31.2×10^6 kw-hrs
- Fixed cost of electricity = $\$0.23 \times 10^6 / 31.2 \times 10^6$ kw-hrs = 0.74¢/kw-hr
- Operating cost = 0.50¢/kw-hr
- Cost of producing waste-heat electricity = 1.20¢/kw

4.2 Single Family Detached Residences

The preliminary screening of solar system concepts identified two major application areas in the single-family detached residences - solar domestic water heating, and solar water and space heating.

These two applications will be covered separately in the following paragraphs with the intent of presenting additional information, showing methods of making estimates of economic performance, and discussing some of the design trade-offs involved in implementation.

4.2.1 Domestic Water Heating

From the standpoint of economic potential, solar domestic water heating is the most attractive application in the Village Complex MIUS for several reasons: the load is steady and relatively low in temperature; the "conventional" MIUS water heating is energy intensive (electrical resistance heat), accounting for a significant fraction of the total electrical energy requirement in the MIUS (18% of the annual electrical load); and the solar equipment required is relatively simple compared to other solar applications.

To present an example we will refer to Table 4.2.1 which summarizes pertinent data and assumptions relating to domestic water heating in a conventional MIUS single family residence. In this case the annual load corresponds to an average usage of approximately 115 gallons/day. Although there will be some seasonal differences in the usage patterns, they are generally relatively small, so that for our purposes we may consider the load to be seasonally steady. If we assume that the average efficiency of an electric water heater is in the range of 90-95% and the cost of electricity is 4¢/KW-HR, the annual charge for conventional electric water heating would be about $390.

As shown schematically in Figure 3.4.1 above a solar water heater (one tank system with resistance heat input to tank) or be a preheat system (two tank system, where resistance heat is put only into the "conventional" tank). A selection between these two general concepts involves consideration of design tradeoff issues such as the capital cost savings associated with one storage tank in place of two, the influence on collection efficiency of storage temperature, the time scheduling of auxiliary electrical heat input to the tank (load management), and others. We will consider the solar water preheating (two storage tank) system in the discussion that follows.

For illustrative purposes, we will consider the solar water preheating system operating in the Washington, D.C. area. The results were based on the use of the performance curves presented in Figure 3.4.5 for a baseline solar collector and the computation approach presented in Appendix B. Figures 4.2.1 and 4.2.2 illustrate technical and economic performance characteristics of the solar water preheaters. As shown in Figure 4.2.1 the percent solar increases with collector area.

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TABLE 4.2.1

ASSUMPTIONS RELATING TO
CONVENTIONAL WATER HEATING IN
SINGLE FAMILY DETACHED RESIDENCE

• Load:	31.6×10^6 Btu*
• Cost of electricity:	4¢/kwh
• Efficiency of conventional water heater:	95%
• Conventional energy cost:	$390

* Corresponds to an average usage of approximately 115 gallons per day.

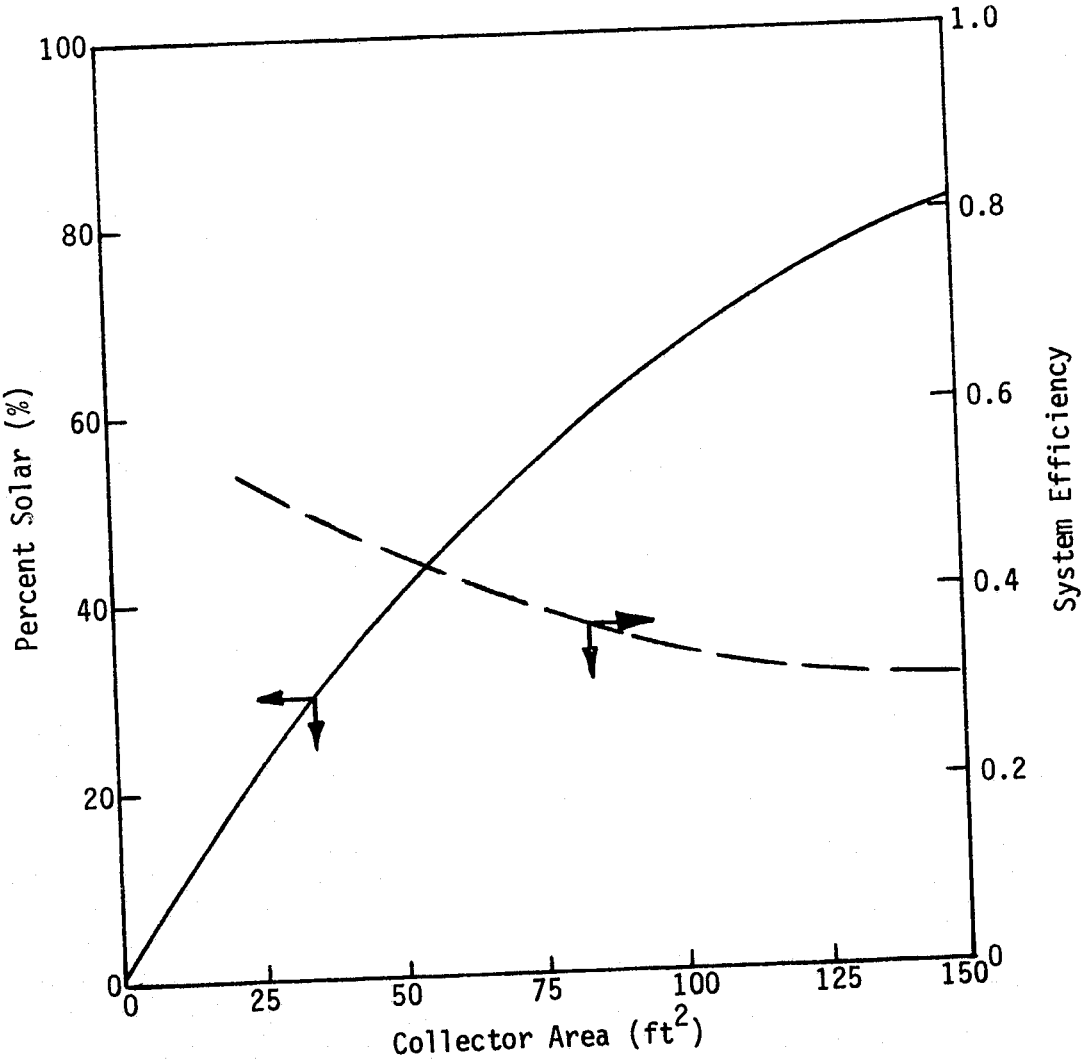


FIGURE 4.2.1

TECHNICAL PERFORMANCE CHARACTERISTICS OF

BASELINE SOLAR WATER PREHEATER; WASHINGTON, D.C.

Since the temperature of thermal storage increases with increasing collector area, the efficiency decreases. Clearly for larger values of the percent solar, the auxiliary electrical demand is lower, resulting in a lower net electric bill to the user. The straight payback period is relatively insensitive to the size of the system, and ranges between 5 1/2 - 6 1/2 years.

The straight payback period is inversely proportional to the cost (to the consumer) of the electrical energy displaced by the solar system. Accordingly, the curve presented in Figure 4.2.2 can be easily revised for alternate assumptions concerning the cost of electricity. The impact of solar water preheating on the MIUS Village Complex is to reduce the net annual electrical energy requirements, thereby realizing a savings in the fuel expended at the generating facilities. During extended periods of cloudy weather, the MIUS will be called upon to provide the full backup, thereby requiring the full reserve generating capacity. However, the two tank (solar preheat) system discussed above allows an option of load management, that is, the scheduling of auxiliary electrical energy input to the conventional water tank at times convenient to the MIUS, such as during off-peak demand periods.

A number of issues would need to be addressed in a detailed analysis of the impact of solar water heating on the MIUS. These issues include: exact orientations of collectors on roof or walls with respect to South and the horizontal, types (designs) of collectors used, prevention of freeze-up by uses of anti-freeze solutions or self-draining collectors, separation of potable water from liquids used in the solar collector loop, prevention of corrosion, etc...

4.2.2 Domestic Water and Space Heating

Assuming a seasonal performance factor (SPF*) of 2.0 for the heat pumps used in the MIUS single family units, space heating accounts for more than 15% of the MIUS annual electrical load, and about 58% of the winter electrical load. Hence, the impact on MIUS of solar space heating in the single family residence.

Figure 3.4.2, shown earlier, illustrates a possible arrangement of the solar system using the conventional heat pump as a backup. In the arrangement shown the heat pump may supply heat to the building from one of two sources: from outside air with an air-air heat pump (Mode 1 operation), or from thermal storage using a water-air heat pump (Mode 2 operation). Using thermal storage as a heat source may appear attractive because of the higher COP's achieved at the higher source temperatures offered by thermal storage. However, in this configuration, the removal of heat from storage by the heat pump lowers the average temperature of thermal storage, thereby diminishing the ability of the solar system to deliver heat directly to the building. In this

* Total heat pump output over a complete seasonal period divided by total energy input to the system, including resistance heating during those intervals that the heat pump cannot satisfy the demand.

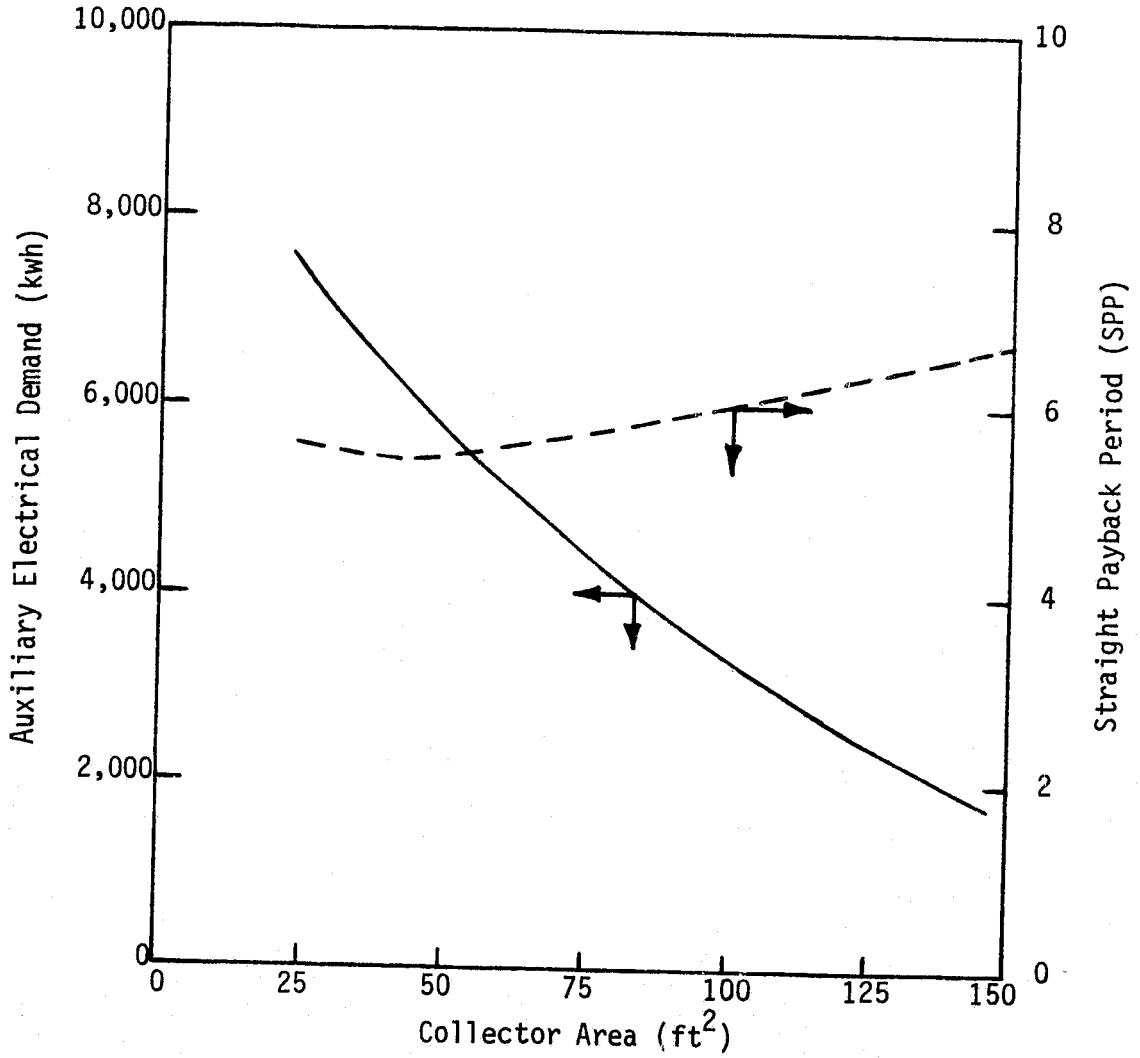


FIGURE 4.2.2

ECONOMIC PERFORMANCE CHARACTERISTICS OF BASELINE SOLAR WATER PREHEATER; WASHINGTON, D.C.

case, the heat pump is required to meet the deficit.

Figure 4.2.3 schematically shows the energy flows in a heat pump. The relationship between the heat withdrawn from the source and the heat input from the heat pump is as follows:

$$Q_2 = Q_1 + W$$

where:

Q_1 = heat withdrawal from the source (to the evaporator)

Q_2 = heat output (from the condenser)

W = compressor work.

These quantities may be related to one another through the coefficient of performance:

$$Q_2 = (W)\ (COP)$$

$$Q_1 = (COP-1)\ (W) = \frac{COP-1}{COP}\ Q_2$$

Using the ADL computer simulation programs, we have carried out, as a part of this project, several case studies for solar water and space heating in the MIUS single family residences. The parameters varied in the case studies were collector area, interface between the solar system and the heat pump (selection of operational mode), and the use of heat recovery from wastewater to supplement heat input to thermal storage:

Case	Collector Area (ft^2)	Mode Selection	Wastewater Recovered Heat (10^6BTU)
1	200	1	---
2	400	1	---
3	400	2	---
4	400	2	14.5

Case 4 supplements an analysis carried out earlier by the NASA USPO*. The conditions for the solar heating studies are summarized in Table 4.2.3.

Assuming an electric cost of 4¢/KW-HR, the conventional utility bill for domestic water and space heating would be about $700, with a heat pump used for the conventional space heating. If only electric resistance heat were available, the yearly water and space heating electric bill would be almost $1,100.

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* "Advanced Heat Pump Study", Urban System Project Office, Lyndon B. Johnson Space Center, March, 1974.

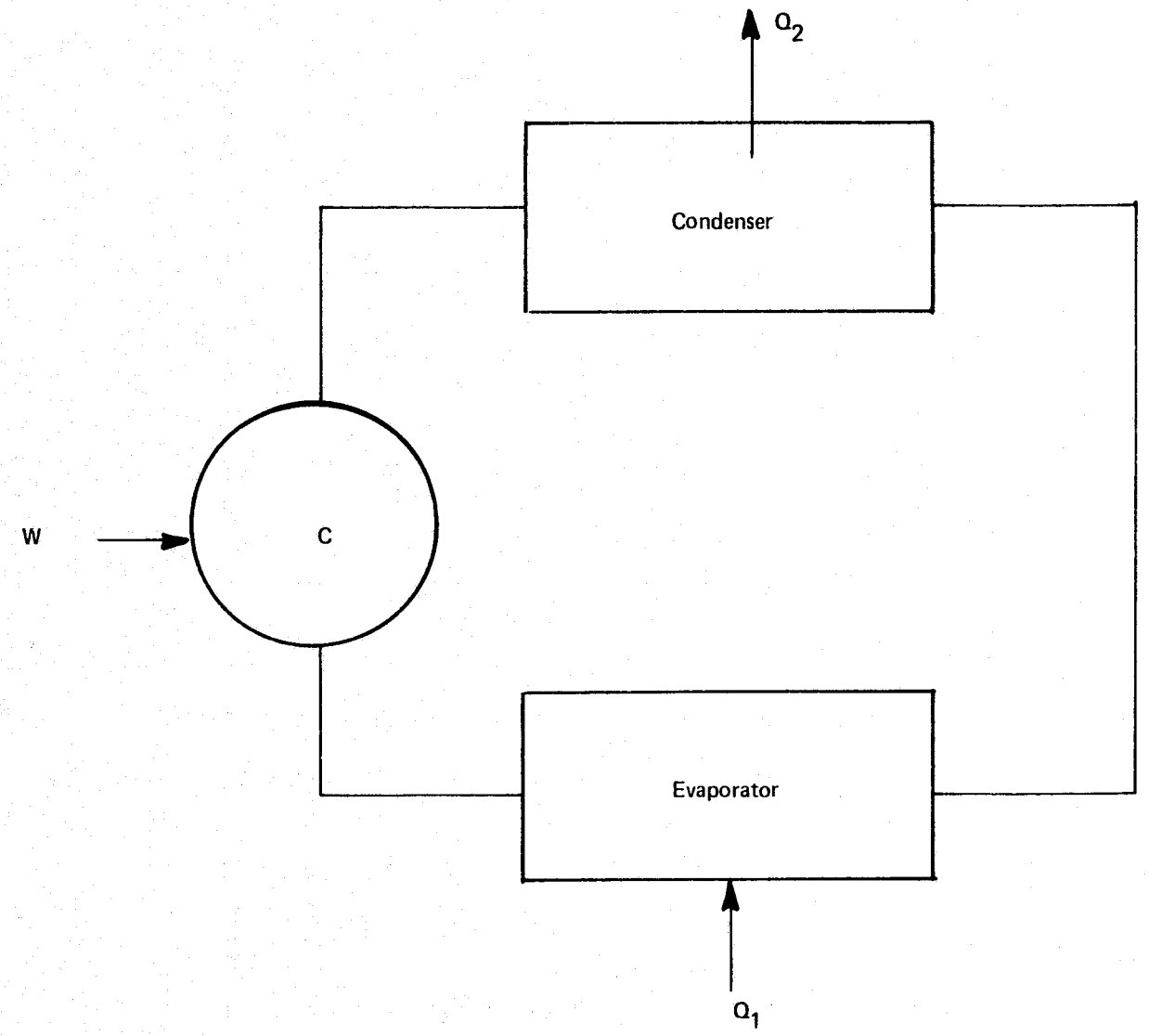


FIGURE 4.2.3 ENERGY FLOWS IN HEAT PUMP

TABLE 4.2.2

Solar Water Heating

- Annual flux: 0.56×10^6 Btu/ft^2 - yr
- Select Q_i/load
  - → Collector area, A
  - → % 5, from performance curves
  - → $\overline{\eta}$, system efficiency
  - → solar energy collected and used
- Solar collector loop pump: $\approx$ 2 kwh/10^6 Btu collected
- Calculate auxiliary energy expenditure
- From collector area, find system capital cost
- Calculate SPP

The heating load shown in Table 4.2.3 is slightly lower than that listed earlier for the single family residence in Table 3.4.1. In our case studies, we simulated the thermal behavior of the building using specified building design parameters and actual hourly weather data for Washington, D.C. The small difference in the computed annual heating load and loads listed in MIUS documentation will not affect the basic results of the analysis discussed below.

For our analysis, we assumed the use of a fairly large heat pump (about 100,000 BTU/Hr capacity). The balance point, where the single family heat load equals the capacity of the heat pump, is below zero. Our analysis took into account the variation of capacity and COP with source temperature based on data for a G.E. heat pump (Table 4.2.4). The dependence of heat pump performance parameters on source temperature is illustrated in Figures 4.2.4 and 4.2.5.

Figure 4.2.6 presents monthly average air temperatures for Washington, D.C., and the heating and cooling degree-days. The actual heating and cooling loads experienced by the buildings' HVAC system are shown in Figure 4.2.7. The peak loads occur during the winter and summer months, with the annual heating load approximately twice as large as the domestic water load. We show the cooling load also, for the sake of completeness, although the solar system does not contribute to satisfying this load.

Figure 4.2.8 illustrates the monthly solar energy incident on the collector* and the collector efficiency as it responds to the flux available and the building load. The collector efficiency is shown for the case study, defined above. Generally, the flux is highest in the summer months; in the months of November, December, and January the monthly flux levels are only about 50% of the peak summer levels. On the other hand, the collection efficiency is highest in the winter because the loads are highest in the winter, thereby resulting in a lower withdrawal of the collected energy from thermal storage. This trend is highlighted by Figure 4.2.9 showing the monthly maximum, average, and minimum storage temperatures. The maximum temperature level allowed in the case studies was 212°F.

Figure 4.2.10 illustrates the monthly values of the percent solar index--the fraction of the load met by collected solar energy. In agreement with the results shown for the monthly storage temperature, the monthly percent solar values are highest in the summer and lowest in the winter. Except in the summer, when the heating load is zero, the percentage of the domestic water load met by the solar system is higher than that of the heating load. Hence, a sizeable fraction of the total operating cost expenses is accounted for by the solar domestic water heating.

---

* Assumed facing South and tilted from the horizontal at an angle equal to the local latitude (38.8°).

TABLE 4.2.3

Conditions for Solar/Heat Pump Analysis

HW Load:	31.6×10^6 Btu
Heating Load:	52.3×10^6 Btu
Conventional Electricity Cost:	4¢/Kwh
Conventional Utility Bill:	$1,095 - Resistance Heat
	$ 701 - Heat Pump*
Design Capacity:	100,000 Btu/hr
Balance Point:	-7.7°F

*SPF = 2.0, computed using the ADL computer models.

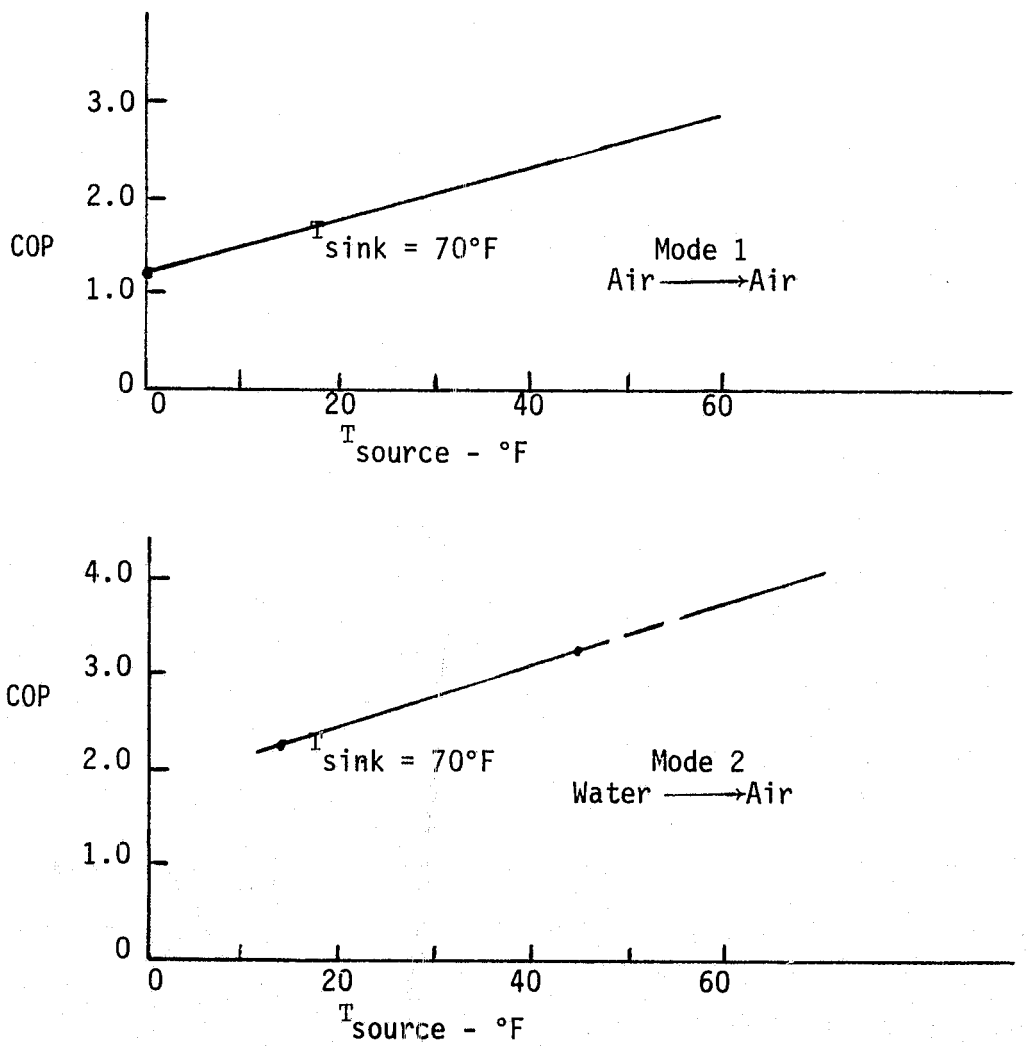


FIGURE 4.2.4

INFLUENCE OF TEMPERATURE ON HEAT PUMP COP

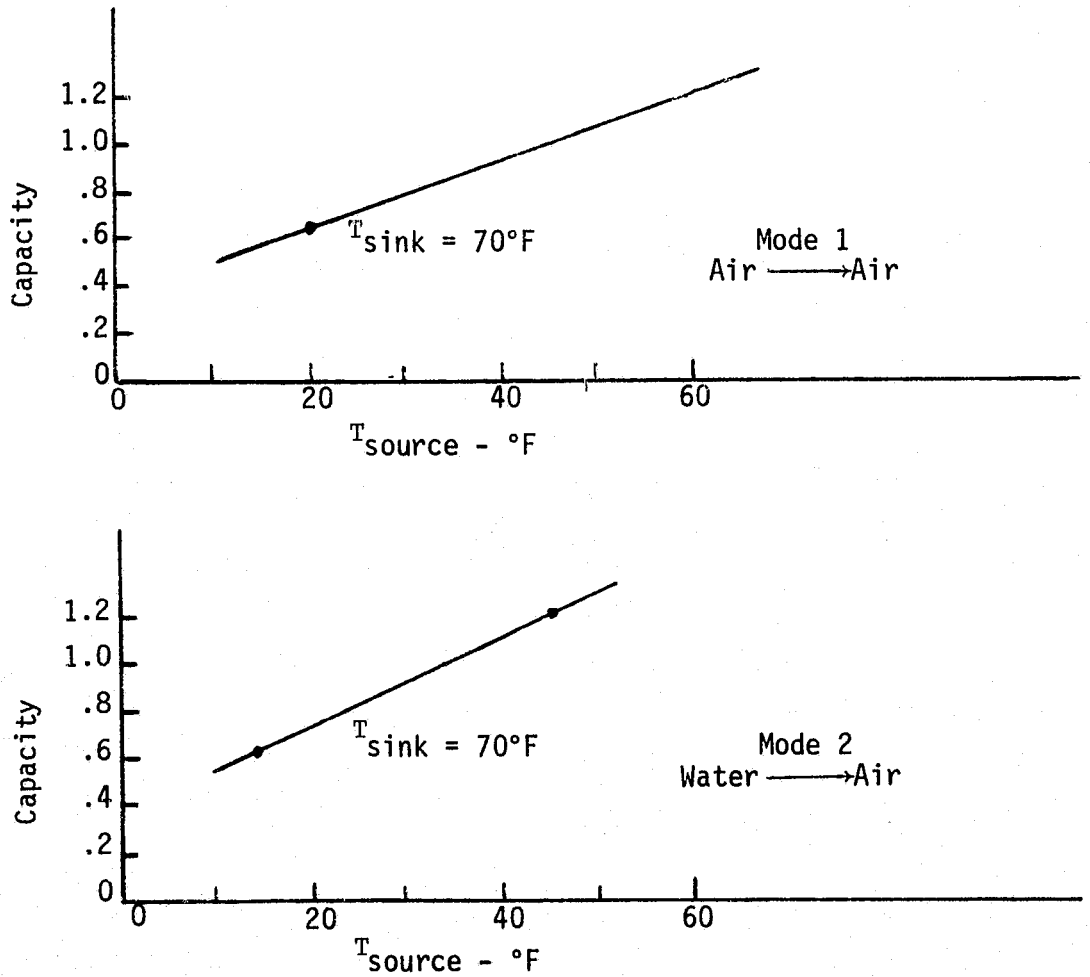


FIGURE 4.2.5

INFLUENCE OF TEMPERATURE ON HEAT PUMP CAPACITY

TABLE 4.2.4

Heat Pump Data*

	Mode 1 (Air to Air)	Mode 2 (Water to Air)
Design Source Temperature (°F)	45.0	34.0
Variation in Capacity with Source Temperature (%/°F)	1.5	2.0
Design COP	2.53	2.88
Variation in COP with Source Temperature (%/°F)	1.0	1.3

Source: General Electric Co.

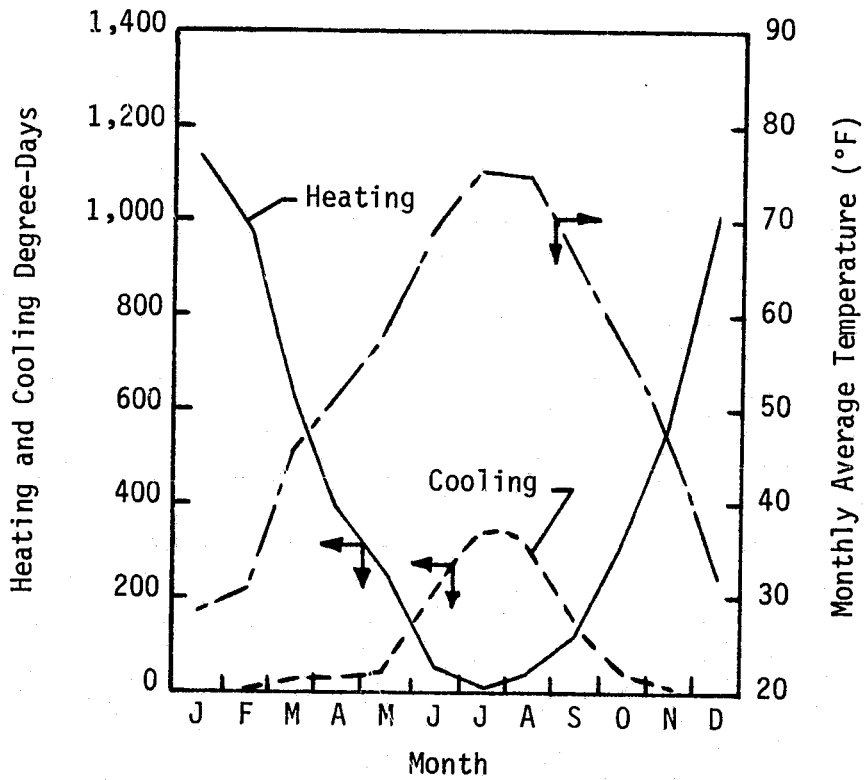


FIGURE 4.2.6

CLIMATE DATA, WASHINGTON, D.C.

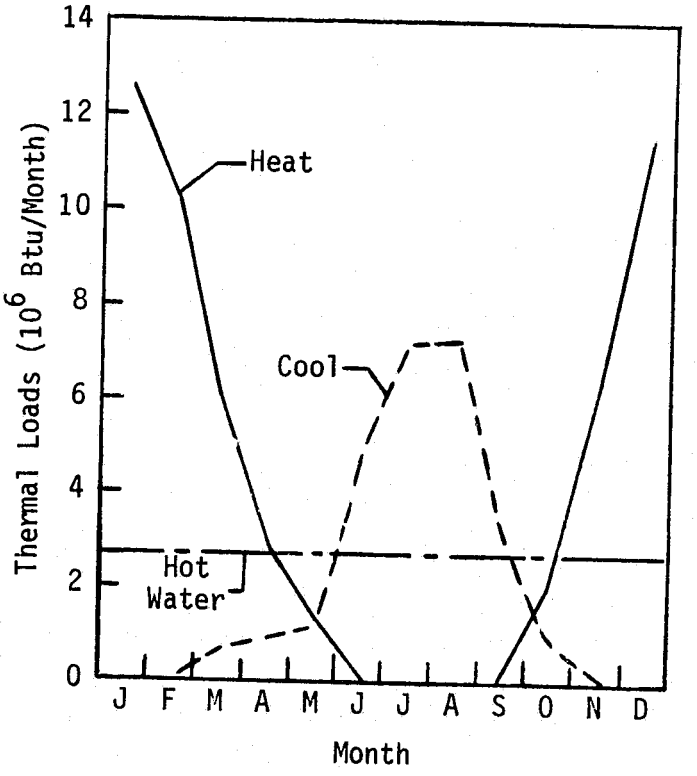


FIGURE 4.2.7

SINGLE FAMILY RESIDENCE MONTHLY LOADS

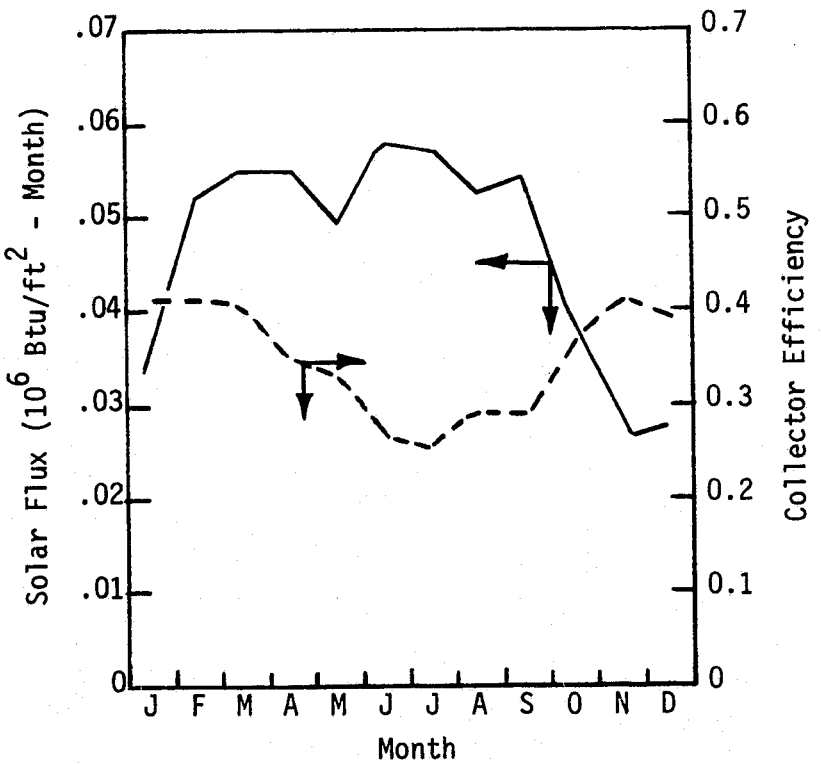


FIGURE 4.2.8

MONTHLY SOLAR FLUX AND COLLECTION EFFICIENCY, CASE 1

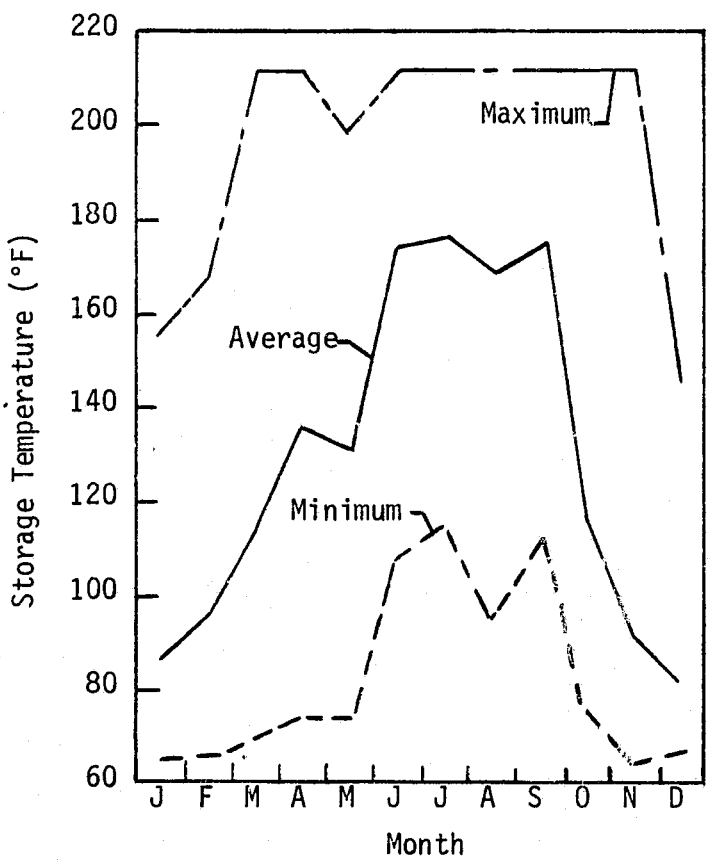


FIGURE 4.2.9

MONTHLY STORAGE TEMPERATURES, CASE 1

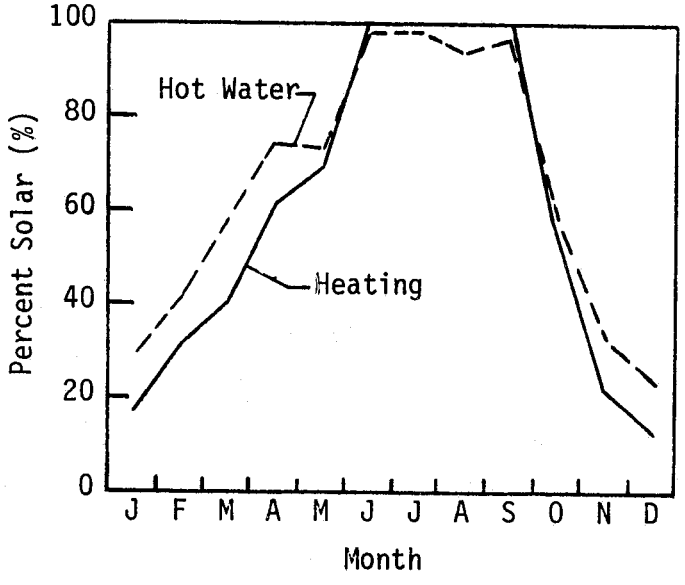


FIGURE 4.2.10

MONTHLY PERCENT SOLAR VALUES, CASE 1

Figure 4.2.11 shows the monthly thermal energy budget--the total hot water and heating loads, and the amounts supplied by the solar and conventional systems. The auxiliary energy shown is the BTU equivalent. With the heat pump used to meet the auxiliary space heating load, the corresponding electrical energy usage is lower.

Table 4.2.5 summarizes the important numerical results for this and the remaining three case studies. For Case 1, the heat pump COP and SPF are approximately equal to 2. For the assumed electrical energy cost (4¢/KW-Hr) and the solar system capital cost $\$12/Ft^2$) the payback period is about 7 years. If all the single family residences in the complex were identical, the total annual reductions in electrical energy requirements would be about 18,400 MW-Hrs, or about 16% of the total MIUS demand. With a larger system (Case 2), the reduction in yearly electrical energy demand is even larger, totaling 24,600 MW-Hrs, or 21% of the total MIUS demand. However, the payback period is longer (9.6 years vs. 7.0 years), because of the decrease in system efficiency with the higher thermal storage temperatures.

Case 3 examines the substitution of a water-air heat pump using thermal storage as the heat source in place of the air-air heat pump considered in Case 2. To prevent undercooling of the incoming "city" water the heat pump was not allowed to lower the temperature of thermal storage below 60°F. When this condition was reached, electrical resistance heating was called upon to supplement the solar system. The results are striking when the COP and SPF values are compared with those for Case 1 and 2. The COP is nearly double because of the higher average source temperature and the lower temperature drop across the evaporator coil; however, the SPF is lower, because of the large percentage of the time that resistance heating is needed to supplement the heat pump. As a result the payback period is relatively long, and the least electrical energy savings result. If, however, a source of "free heat" is available to supplement the solar collector--such as recovered wastewater heat--then the operating economics are more attractive. In Case 4, we consider that 14.5×10^6 BTU of recovered heat* is available to serve as a heat source to the heat pump--an amount equal to 27% of the solar collected heat. In this instance, the SPF increases by about 36% over the Case 3 value, and the total electrical energy saved is increased to a value achieved with the air-air heat pump arrangement. When we compare the Case 2 and Case 4 results, we find that the performance indices are nearly the same. Hence, in the absence of a large source of "free" heat, the air-air arrangement would appear more attractive than the water-air arrangement.

A major issue to be resolved with solar/heat pumps system is the impact on peak loads. Both the heat pump and solar system are energy conserving devices which may reduce electrical consumption considerably, but which require near full auxiliary (I^2R) backup because of the drop off in heat pump capacity with low temperature, and

* About equal to the waste heat available assumed in Reference 10.

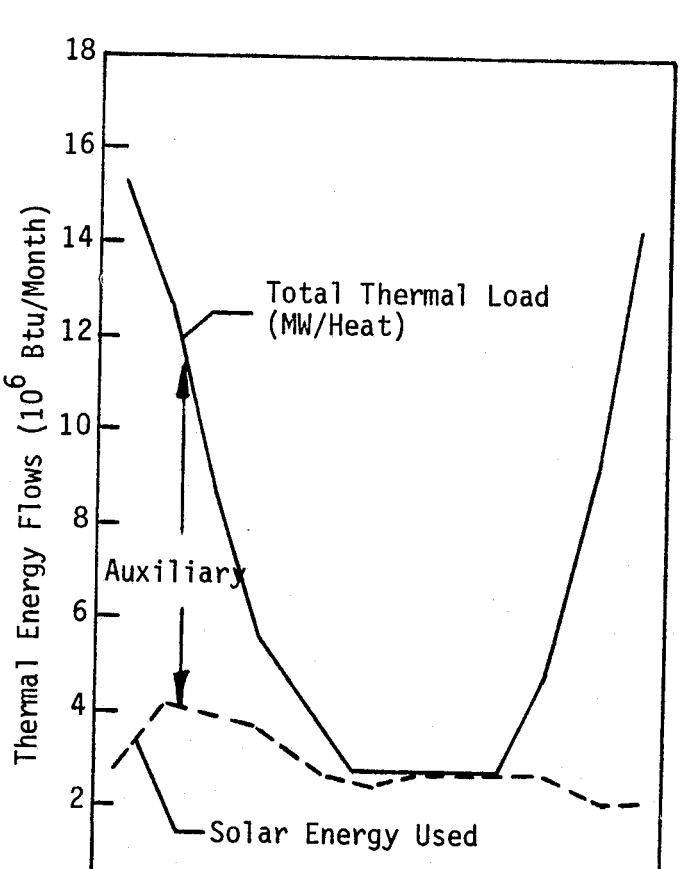


FIGURE 4.2.11

MONTHLY THERMAL ENERGY BUDGET--SOLAR AND AUXILIARY, CASE 1

TABLE 4.2.5

Heat Pump Analysis Results

	Case 1	Case 2	Case 3	Case 4
Collector Area (ft^2)	200	400	400	400
SCC Capital Cost ($)*	2,400	4,400	4,400	4,400
Heat Pump Configuration	air-air	air-air	water-air	water-air
Recovered heat to storage (10^6 BTU)	---	---	---	14.5
System Efficiency	.32	.23	.24	.24
Average Storage Temperature (°F)	129	152	146	152
Percent Solar				
-- hot water	65	74	71	59
-- heating	28	53	60	64
-- combined	42	61	64	63
COP	2.1	2.3	4.3	4.4
SPF	2.0	2.3	1.4	1.9
Auxiliary Energy (kwh)	8,900	6,008	9,508	5,935
Energy Cost ($)	345	240	381	237
Straight Payback Period (yrs)†	7.0	9.6	13.7	9.5
Total kwh saved:	8,625	11,517	8,000	11,600

*SCC Capital Cost/Area = $\$12/ft^2$ for 200 ft^2 system; $\$11/ft^2$ for 400 ft^2 system

†Does not include value of energy savings to utility

the drop off in solar system capacity with extended cloudy weather. The solar/heat pump system arrangements discussed above do not contribute to solving the peaking problem. However, other system arrangements are feasible that can facilitate load management. For example, Figure 4.2.12 is one such system, where a separate "utility" hot and cold storage unit is provided. In this arrangement, the heat pump may supply heat directly to the building using outside air as a heat source or using the utility storage as a source; the heat pump may also be used to put heat directly into the storage unit during off peak hours. Finally, the separate storage may be used in conjunction with off-peak air conditioning. Many other system arrangements are possible. Selection of the solar/heat pump systems arrangement most favorable to the MIUS would involve additional analysis. However, such a system would appear to be a prime candidate for inclusion in the MIUS.

4.3 Central Combined Heating and Cooling for High Density Limits

Central station collection of solar heat is characterized by a relatively steady collection temperature. For heating, collection occurs in the range of 170-190°F; for cooling, collection occurs in the range of 210-240°F. Table 4.3.1 summarizes characteristic features of central solar collection.

High-performance collectors are currently not marketed although several are under development. Some of the more notable concepts, capable of achieving efficient high temperatures collection, are listed in Table 4.3.1. When high-performance collectors do become available, it is expected that the initial costs will exceed $\$15/Ft^2$, possibly less as the market develops.

It is conceivable that a central collection system might not require a large thermal storage subsystem. In this instance the collected heat would be directly introduced into the hot water distribution line or used for activating the absorption refrigeration equipment. For a very large system that would be capable of meeting a large fraction of the total MIUS HVAC load, thermal storage would be required to maintain a relatively stable collection temperature, and hence, high collection efficiency. However, as discussed in Section 3.5 the land area available in the Village Complex would rule out a system this large. With a small requirement for thermal storage the system capital cost would be mostly accounted for by the solar collector cost.

Figure 4.3.1 illustrates calculated (using the ADL solar simulation computer models) values of annual collection efficiency versus collection temperature for high performance collectors. Curves are shown both for a stationary collector and a tracking collector. Collection efficiency is defined on the basis of the annual solar flux incident on the collector. With tracking a collector, both the incident flux and collection efficiency are higher than for a stationary collector.

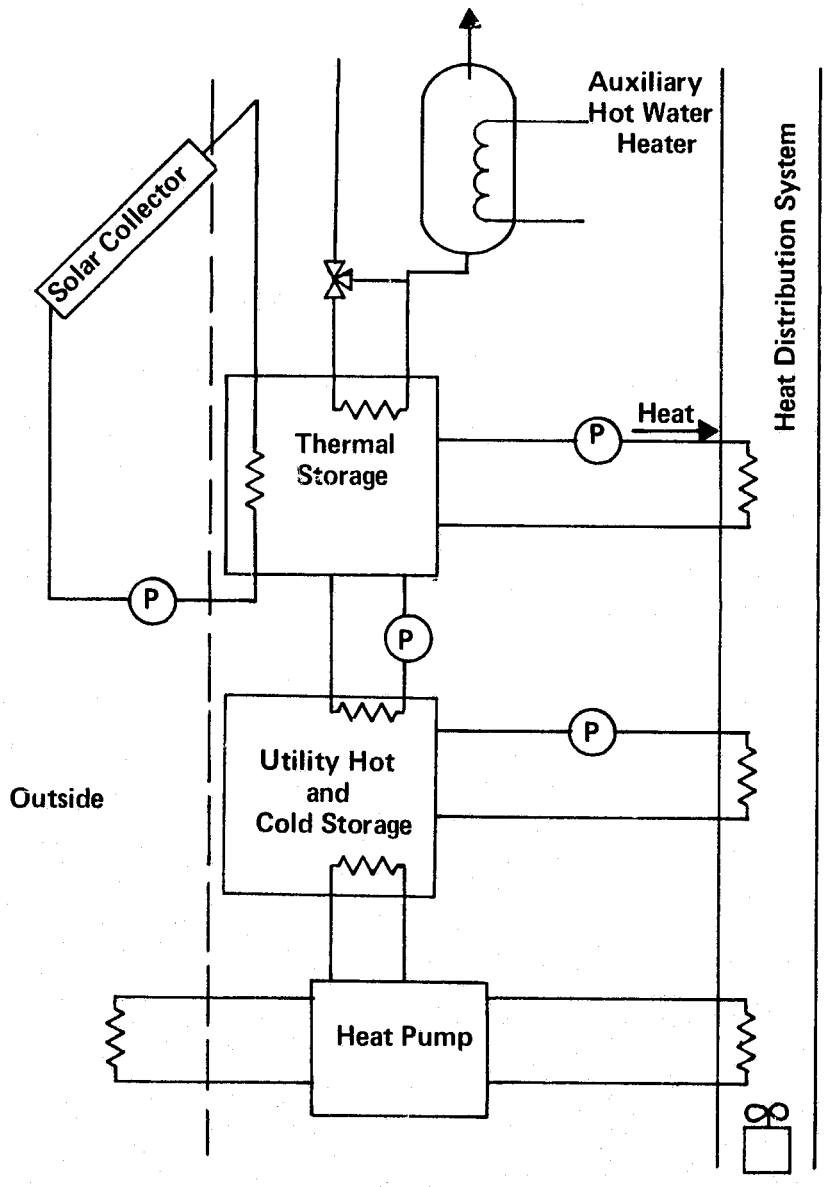


FIGURE 4.2.12

SOLAR WITH PARALLEL HEAT PUMP AND STORAGE

TABLE 4.3.1

Central Station Solar Collector

- Fixed Temperature Collection (170 - 240°F)
- Efficiency independent of size
- High-performance (concentrating) collectors currently under development:

  Argonne - "concentrating parabolic collector"

  Corning Glass Works - evacuated tube

  Northrup - Fresnel lens

- System capital cost per unit collector area independent of size, approximately $\$15/ft^2$
- Tracking mechanism assumed to be small fraction of total cost

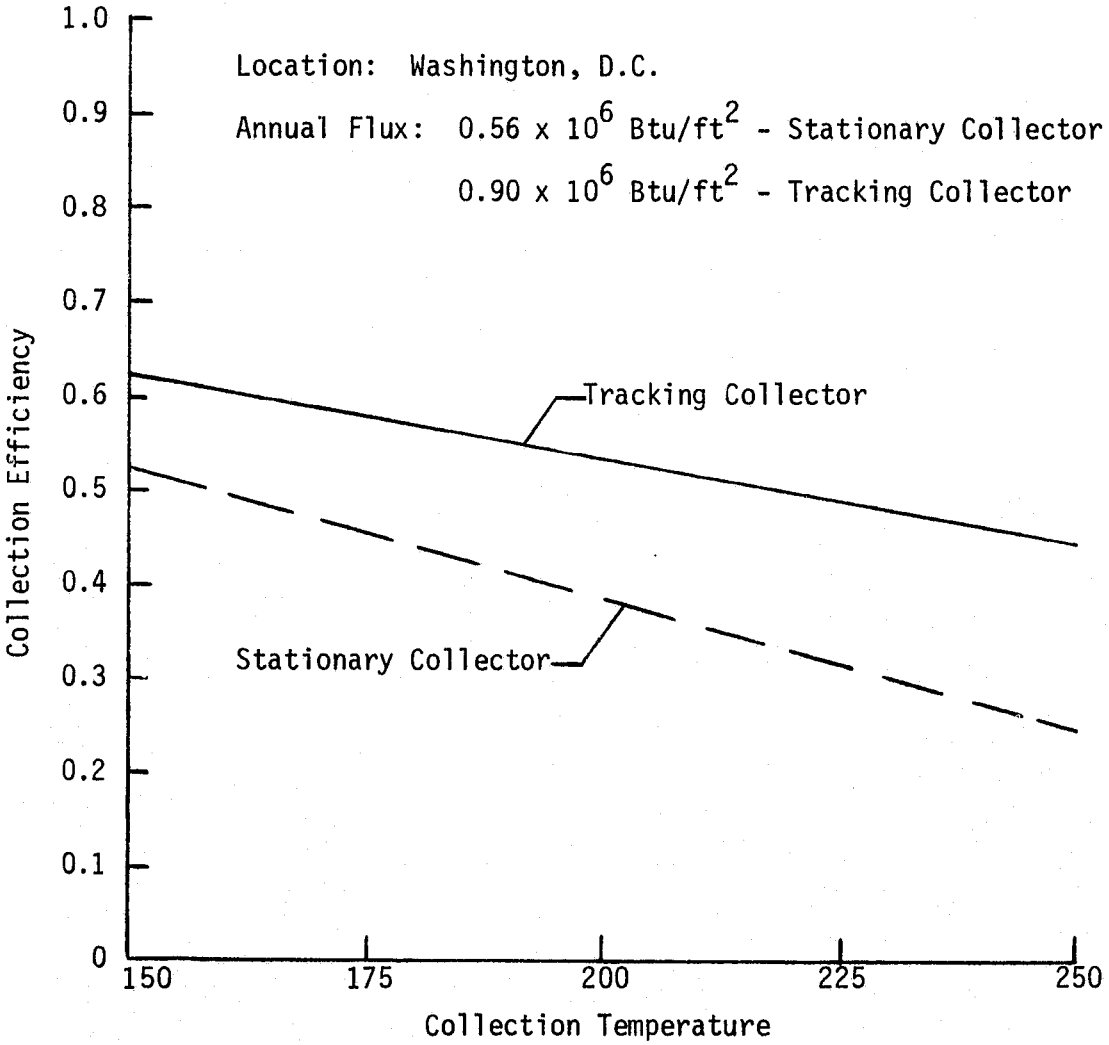


FIGURE 4.3.1

ANNUAL COLLECTION EFFICIENCY VS. COLLECTION TEMPERATURE FOR HIGH-PERFORMANCE COLLECTORS

Table 4.3.2 summarizes the economics of central solar collection. If used only for delivering heat to the MIUS hot water distribution system the stationary collector will supply 0.26×10^6 BTU of heat per square foot of collector area, with a resultant heat cost of $\$5.8/10^6$ BTU. The tracking collector would collect essentially twice as much heat, and, for the same system capital cost, yield an annual average solar heat cost of $\$2.8/10^6$ BTU. If, on the other hand, the collector were used only to supply heat at 210°F to drive absorption chillers, the cooling produced would be 15 and 31 ton-Hrs/Ft^2 of stationary and tracking collectors, respectively. If the absorption cooling replaced only electric vapor compression cooling, the net electrical energy reductions would be about 12 and 24 KW-Hr/Ft^2 of collector area. With a 10% amortization rate and a $\$15/Ft^2$ system cost, the central solar cooling would pay for itself if the cost of conventional electricity were either 13¢/KW-Hr or 6¢/KW-Hr, depending on the collector used.

Central collection would be economically viable only if the system costs assumed in the analysis above were achievable and if the energy displaced by solar heat had "value". That is, any time there is an excess of high temperature heat in the MIUS, the heat displaced by the solar system has no value--no fuel energy savings are realized by the use of the solar system.

Because of the marginal economics for central solar heat collection and because of the requirement for a deficit in MIUS high temperature waste heat, the central station solar collection concept is not an attractive near term application in the MIUS.

4.4 Solar Dehumidification of Individual Buildings Connected to the HVAC Subsystem

4.4.1 The Desiccant Process

Desiccant dehumidification systems utilize materials (desiccants or sorbents) which have the ability of attracting and removing water from an air stream. The desiccant may be either a liquid, such as a glycol compound, or solids, such as lithium chloride or molecular seive material. The water removal process may be either by absorption which involves a physical or chemical change in the desiccant (as is the case with materials such as glycol or lithium chloride) or by absorption which involves no physical or chemical change in the desiccant but generally depends on surface effects (as is the case with molecular seive material).

All of the above mentioned materials remove water by reversible mechanisms and therefore can be regenerated. Although some nonregenerative systems, such as those using hygroscopic salts have value for some applications (generally for small batch process operations), they do not lend themselves to space conditioning.

TABLE 4.3.2

Central Collection Economics

Heating (170°F)	Cooling (210°F)
System Cost: $\$15/ft^2$	System Cost: $\$15/ft^2$
Heat delivered:	A/C COP
- stationary: 0.26×10^6 BTU/ft^2	- absorption: 0.7
- tracking: 0.53×10^6 BTU/ft^2	- vapor compression: 4.5
	Cooling produced
	- stationary: 15.2 ton-hr/ft^2
Solar Heat Cost*	- tracking: 30.9 ton-hr/ft^2
- stationary: $\$5.8/10^6$ BTU	
- tracking: $\$2.8/10^6$ BTU	Electrical energy reduction
	- stationary: 11.9 kwh/ft^2
	- tracking: 24.2 kwh/ft^2
	Equivalent value of cooling*
	- stationary: 12.6¢/kwh
	- tracking: 6.2¢/kwh

*Assumes 10% amortization rate

The basic regenerative dehumidification cycle includes two elements:

(1) Sorption, or removal of water vapor from the air stream into the desiccant. This process generates heat, the major portion of which is the heat of condensation of the water vapor. Means of heat removal must be provided either with an external coolant, or by accepting the rejected heat as temperature rise in the process air. The lower the temperature of the sorption process, the lower the attainable air dew point.

(2) Regeneration, or the removal of water from the desiccant. Regeneration must be accomplished by heat addition--either in the form of heating coils and/or a warm regenerative gas stream. The degree of sorbent drying is proportional to the regeneration temperature.

The basic ways in which desiccant systems can be applied to air conditioning include:

1. Improved comfort through lowering relative humidity alone.
2. Serve as a preconditioning step which lowers the latent heat load on the refrigeration type air conditioner. This preconditioning allows the refrigeration type air conditioner to operate at both a reduced load and at a higher evaporator temperature.
3. Achieve cooling as well as dehumidification by overdrying the air and then rehumidifying it to achieve the desired temperature and relative humidity.
4. Desiccant enthalpy exchangers can accomplish latent, as well as sensible heat recovery between inlet ventilation air and discharge air.

A coefficient of performance for regenerative desiccant systems can be defined as the ratio of latent heat removal to regenerative heat addition. As a theoretical limit, one might expect the coefficient of performance to approach unity--i.e., regenerative heat addition just equal to heat of evaporation.

4.4.2 Liquid Absorbents

Liquid absorbent desiccants have a high capacity for water removal and are easily circulated and brought into intimate contact with the process and regeneration streams. Liquid absorbents such as tri-ethylene glycol have been used in commercial systems for dehumidification of inlet ventilation air for space conditioning applications and other process uses. These systems tend to function most effectively in high humidity regions. In order to achieve dew points low enough for comfort cooling, the absorber chamber must be cooled with cooling tower water. (In some instances, well water, or even refrigerated coolant water is required to achieve sufficiently low dew points.)

Commercial liquid absorbent systems are manufactured by Niagra Blower, Midland-Ross and others. An experimental solar hot air driven liquid absorbent machine illustrated in Figure 4.4.1 operated successfully by Löf in the early 1950's. A solar hot-water driven liquid absorbent system is currently being considered for the Citicorp building by an MIT design team[12]

The regeneration temperatures required for liquid desiccant systems are reasonably low. For a non-solar operation a warm water temperature of 175° is generally considered adequate. Löf found his system could operate at, or somewhat below, 175°F. Tests are being run in connection with the MIT/Citicorp project to determine if a commercially available system will function satisfactory at 140°F.

The coefficient of performance of the liquid absorbent machines is about 0.5.

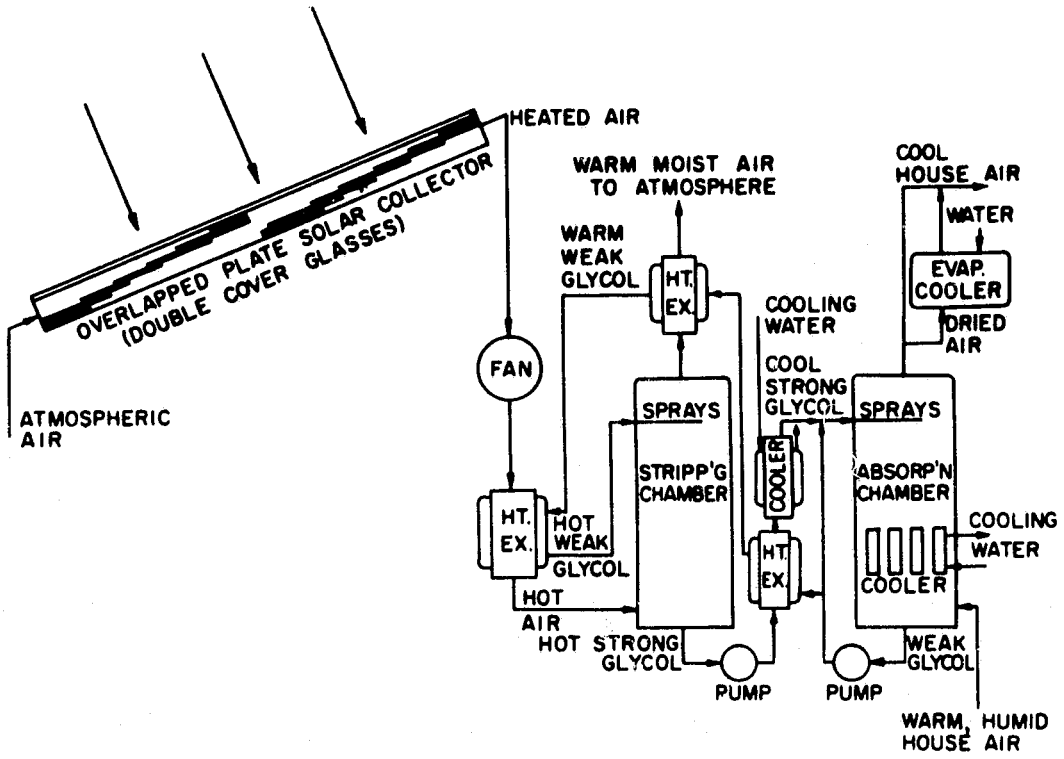
Figure 4.4.2 illustrates the application of a liquid absorption solar dehumidification concept to MIUS. For clarity, the liquid absorbent equipment is shown in very simplified form as a single sump design with a cooled absorption chamber in which the liquid absorbent absorbs water vapor from the inlet (or recirculated) air and a heated regeneration chamber in which the absorbent releases water to a regeneration air stream. (Actual commercial systems may have dual sump with a liquid heat exchanger between the warm absorbent leaving the regenerator section and the cool absorbent approaching the regenerator; a cooled reflux coil in the regenerator section; and various mist eliminators in both regenerator and absorption sections.)

The system shown operates to reduce the humidity of the air stream prior to the basic cooling device--the MIUS chilled water distribution network.

4.4.3 Solid Desiccants

Solid desiccants include both absorbents such as lithium chloride impregnated matrices* and absorbents, such as silica gel and molecular seives. Solid desiccants generally have a lower moisture capacity than the liquids (particularly at high humidity conditions), but further development may extend their capability. Two common mechanical forms of regenerative desiccant equipment are the rotary wheel and the dual (or multiple) bed arrangement. Rotary equipment usually has the greater capacity per unit equipment volume and has usually been favored for space conditioning and similar applications. However, since current commercial applications have tended to stress a lower humidity range and use higher regenerator temperatures than may be optimal for solar driven systems, solar systems may have greatly

* Lithium chloride is designed to operate as a solid absorbent, however, after prolonged exposure to high humidities, lithium chloride can become a liquid solution.



Source: Reference 11

FIGURE 4.4.1 **SOLAR COOLING BY ABSORPTION DEHUMIDIFICATION**

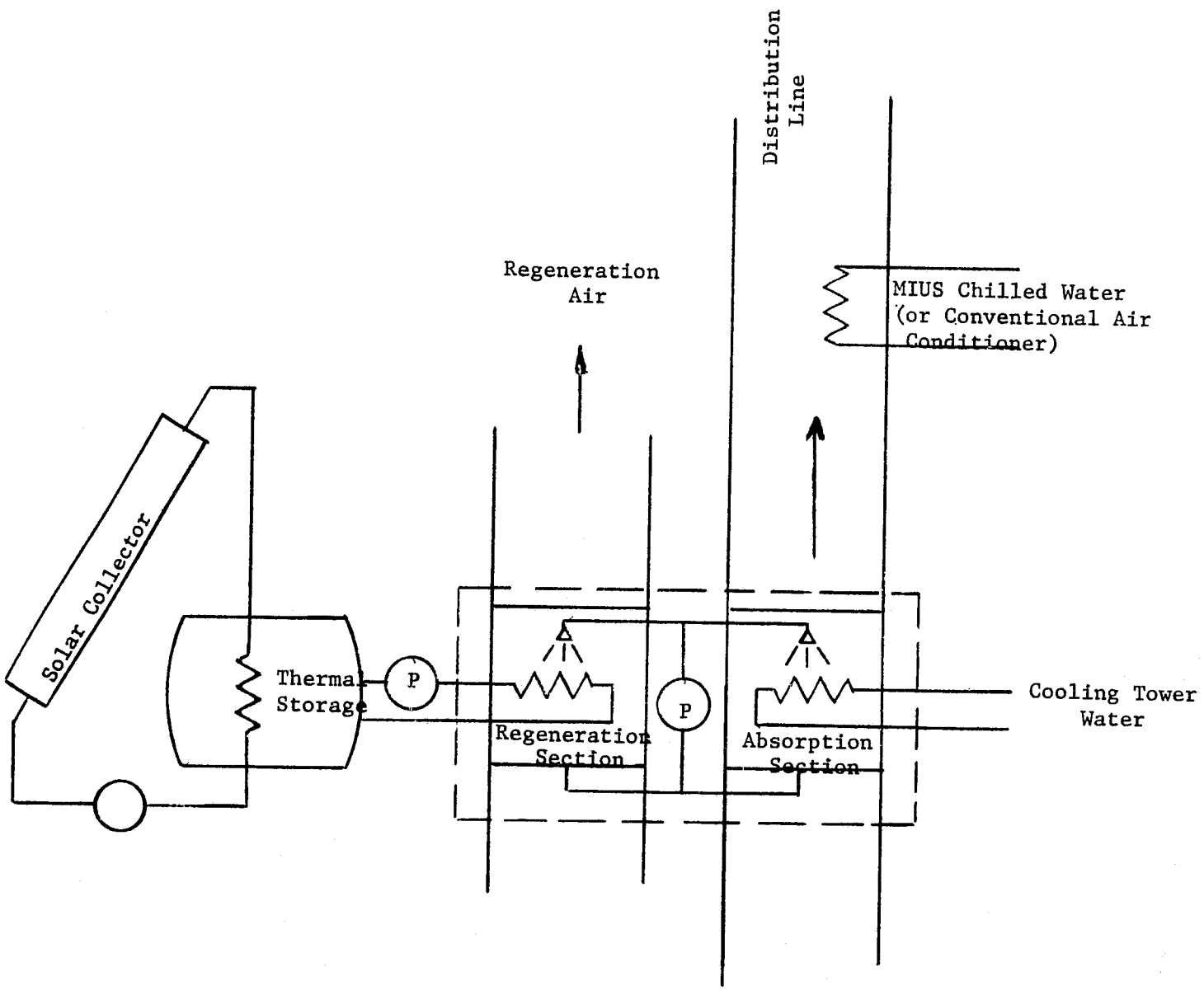


Figure 4.4.2

Liquid Absorbent Solar De-Humidification Concept

different design parameters than existing equipment. For instance, in the silica gel systems which have very high drying capacity, there are indications that systems designed for solar heat regeneration may achieve higher percent useful capacity and longer bed life with the fixed bed geometry rather than the rotary configuration.

Desiccant systems, and solid desiccants in particular, are generally designed to fit the particular application. There is relatively little design information available in the literature to enable one to readily establish the parameters of a desiccant system to fit a new application. The feeling in the industry is that systems designed for solar heat regeneration may be significantly different than those currently existing, and that information such as coefficience of performance, driving temperature, etc. from available equipment may be a somewhat precarious guide to the future. However, to give some insight into current and projected applications, the matrix of Table 4.4.1 indicates typical solid desiccant equipment and current research.

Most of the above applications are designed for large commercial and/or industrial buildings. One exception is the Institute of Gas Technology (IGT) Munters Unit which is designed as a residential heating and cooling unit with a probable size range of from three to ten tons of cooling. Because this unit is a good illustration of some of the many options available with solid desiccant systems, it will be discussed in more detail below.

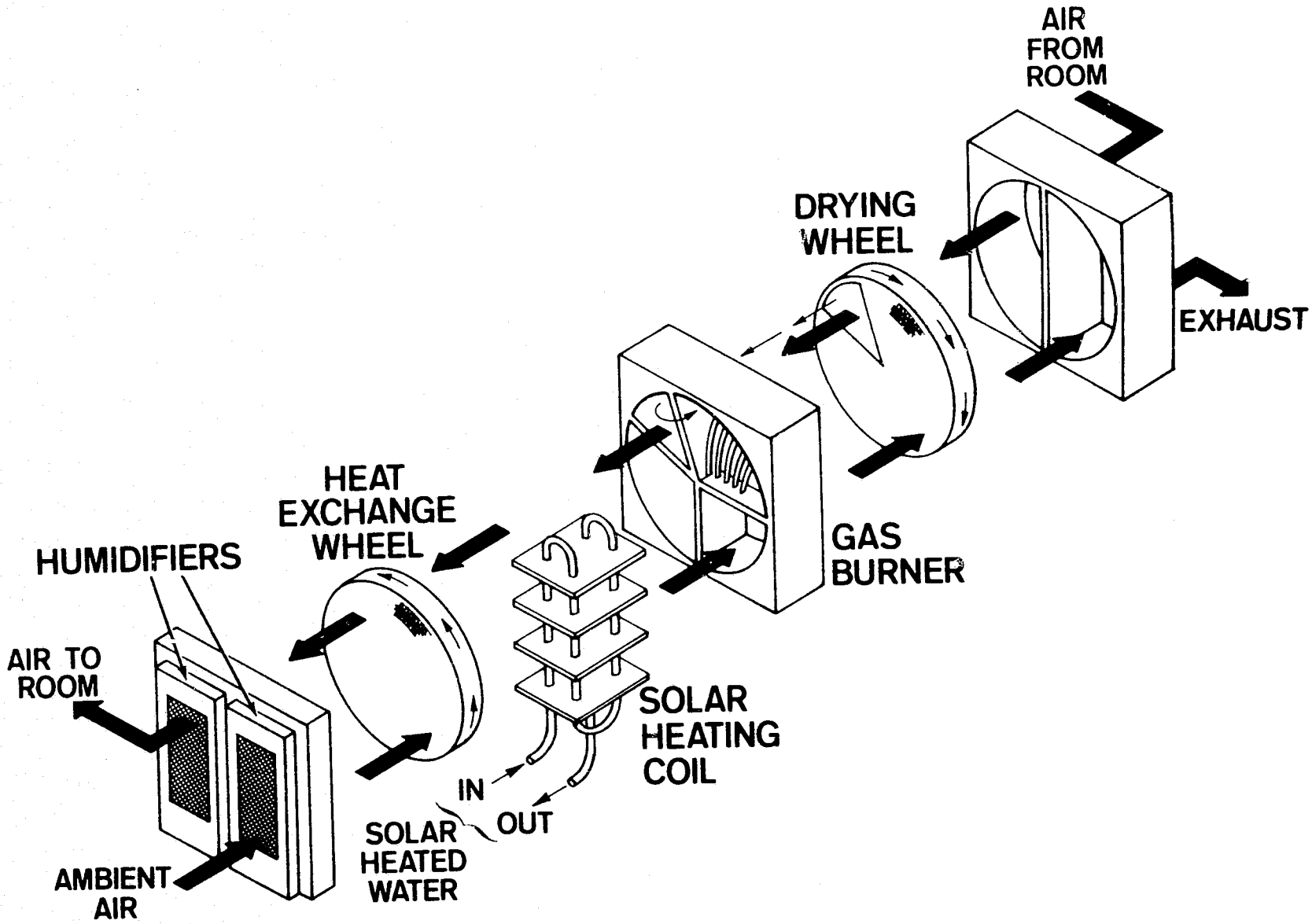
Figure 4.4.3 represents a schematic of the Munters Environmental Control (MEC) 13 unit which uses a rotating desiccant wheel and rotating heat exchange wheel (in conjunction with humidifying sections) in an open cycle cooling (and heating) machine. In the cooling mode shown in Figure 4.4.3, the MEC unit circulates room air and outside air, each confined to a different side of the unit. One side of the MEC processes room air which is in turn dried, sensibly cooled, and evaporatively cooled to reach the desired end state for room comfort. The other side of the unit processes outside ambient air, which is, in effect the sink for the dehumidification and cooling processes performed on the room air.

The room air enters the MEC through a warm molecular sieve drying wheel where it is dehumidified and heated; it next passes through a heat exchange wheel where it is sensibly cooled; and finally through a humidifying chamber where it is further cooled and partially rehumidified, resulting in an end state similar to that achieved in a conventional electric air conditioner. On the other side of the unit, outside ambient air enters through a humidifying chamber where it is cooled by adiabatic saturation; it next flows through the heat exchange wheel where it absorbs the heat which had been removed from the room air; then it is heated (by heat source which may include solar energy); finally, it passes through and regenerates the drying wheel before being exhausted outside.

TABLE 4.4.1

TYPICAL SOLID DESICCANT EQUIPMENT AND RESEARCH

Desiccant \ Configuration	Rotary	Fixed Bed
Molecular Sieve	Solar-gas heating and cooling residential development unit, T=250°F (80% solar) COP= 0.7 (IGT). Available for commercial space conditioning (Bry-Aire, Inc.).	Chemical process industry water and CO_2 removal
Silica Gel	Available for special commercial/industrial space conditioning with T=250°F (175°F possible). Residential design in process (Bry-Aire, Inc.)	Commercial units (C.M. Kemp, Pall-Trinity Micro Corp.) T=250°F
	Solar research T=200°F, COP=0.7 (CEM)	Preliminary solar designs T=175°F (Davidson Chemical)
Lithium Chloride	Commercial units for: (1) Low humidity space conditioning T=250-300°F (2) Enthalpy exchange between inlet and exit (no net heat addition) (Cargo Caire, Inc.)	



Source: Institute of Gas Technology, Press Release, May 20, 1974.

FIGURE 4.4.3 SCHEMATIC OF SOLAR-MEC SYSTEM WITH HEATING/AIR-CONDITIONING UNIT EXPLODED TO SHOW MAJOR COMPONENTS

Although it illustrates many of the components and options which can be achieved with desiccant systems, the IGT MEC unit would probably not be compatible with MIUS in its totality because of the requirement for fossil fuel heat supplement. Also, in many instances, one or more of the humidifiers may not be appropriate --i.e., if the fossil fuel temperature supplement is removed, drying capability will probably be degraded with the result that the air leaving the heat exchange wheel may not be sufficiently dry to allow rehumidification. Also, in other designs, such as the silica gel rotary regenerator design proposed by Lunde 14, the location of regenerative heat exchangers may be different than in the Munters unit.

Figures 4.4.4 and 4.4.5 show rotary solar desiccant concepts using the basic arrangement of components of the IGT Munters design. The version shown in Figure 4.4.4 operates on recirculated air where that of Figure 4.4.5 operates in the 100% fresh air ventilation mode (the extreme case for larger commercial buildings). Conditions intermediate of circulating fresh air and inside air can be achieved by modulating the fraction of inside and outside air entering the unit--or by using multiple units, some recirculating and some with the 100% ventilation.

4.4.4 Solar Desiccant Dehumidification Performance Characteristics

Solar desiccant dehumidification systems have the following characteristics:

- Probably only practical for individual units located at buildings to avoid the necessity of transferring air or concentrated liquid desiccant from the central facility.
- Can provide summer utilization of solar collector design for winter heating.
- If used only for latent load (or portion thereof), the collector will generally be a reasonably small portion of roof area--and perhaps comparable with heating area requirements for commercial buildings. (This point was developed in a prior section.)
- Prior dehumidification allows sensible cooling to occur at a higher chilled water temperature (or evaporator temperature) thereby improving COP of absorption chiller (or heat pump).

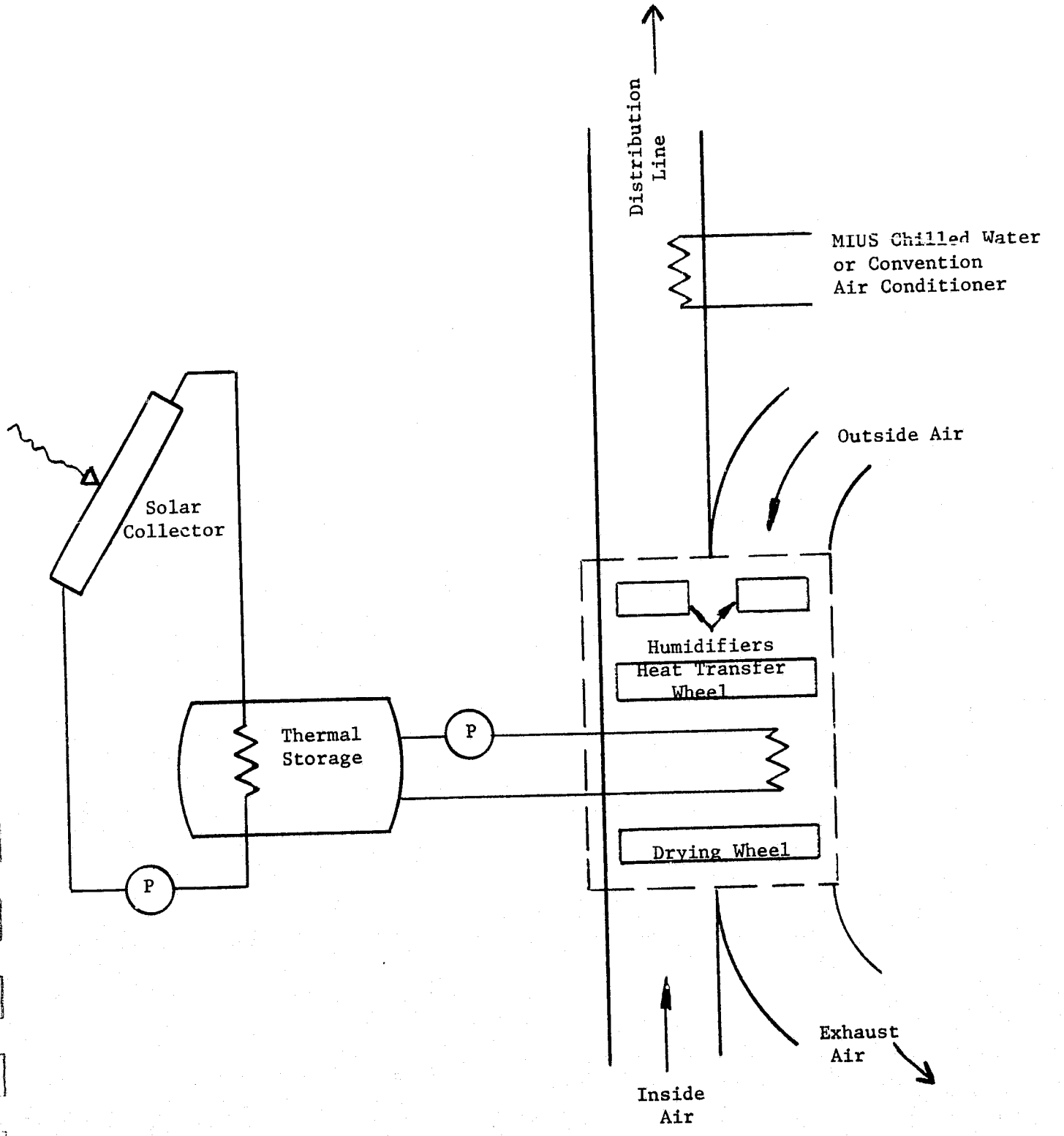


FIGURE 4.4.4 Rotary Solid Desiccant Solar De-Humidification Concept - Recirculation Mode

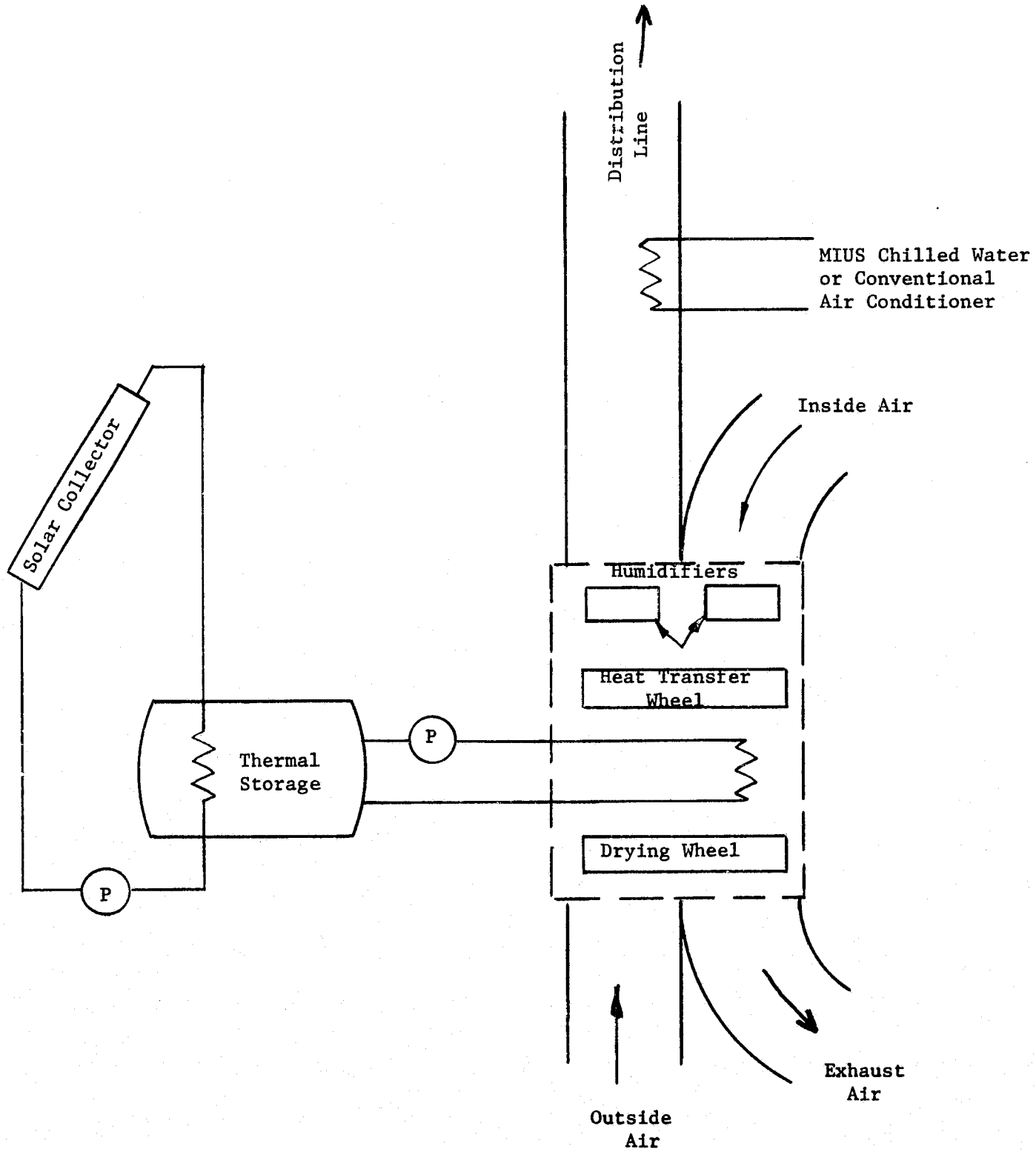


FIGURE 4.4.5 Rotary Solid Desiccant Solar De-Humidification Concept - 100% Ventilation Mode

- COP will generally be comparable to that of absorption machines.
- At least some type of desiccant systems can be designed to operate at temperatures lower than those required for absorption machines.
- Equipment is not yet commercially available for small sizes--i.e., residential units.*
- Best applications appear to be where latent loads are a large fraction of the total air conditioning load (e.g., high school and middle school) and where cooling is required throughout year (e.g., recreation area and commercial center).
- Liquid systems require cooling tower and are probably best matched to larger buildings.
- Single family will probably require an air cooled unit, such as the Munters and other solid desiccant designs.*

A summary of some characteristics of the various desiccants systems is presented in Table 4.4.2.

4.4.5 Evaluation of Desiccant Systems

4.4.5.1 Guidelines and Assumptions

For the individual buildings, the solar desiccant system must compete on the basis of reducing the usage and installed capacity of centrally supplied chilled water. The installed capacity including the prime movers, electric chillers, and associated absorption chillers is assumed to be sized to match the peak summer cooling requirement.

The above rule implies that the solar dehumidification system cannot take credit for heating domestic hot water (at any times other than peak cooling periods)--or for contributing to space heating. It must be a "cooling only"--or "dehumidification only" system. Therefore, to achieve a reasonable utilization, the solar

---

* Although single family use has been excluded from MIUS, these comments are included for general information.

TABLE 4.4.2

CHARACTERISTICS OF DESICCANT SYSTEMS

System	Size	Status	Operating Temperature[1]	COP	Heat Rejection	Drying Regime Temperature/Humidity
Liquid Absorbent	Commercial	Available	140-175	0.5[3]	Cooling Tower	Low/High
Rotary-Sieve	Commercial	Available	175-250		Regenerative	High/Low
	Residential	Development (2-5 yrs.)	250[2]	0.7[3]	Evaporative	High/Low
Rotary-Gel	Commercial	Available	175-250	0.8[4]	Regenerative	Moderate
	Resiential	Development (1 yr.)			Regenerative	Moderate
Rotary-LiCl	Commercial	Available	150-250		Regenerative	High/Low
Bed-Gel	Commercial	Available	150-250		Regenerative	Moderate

Notes:

(1) Low temperatures are estimated values; high temperatures are demonstrated.

(2) Design point temperature for 80% solar.

(3) Based on test.

(4) Based on analysis of Lunde 14.

dehumidification system must be applied to a building which has a reasonably uniform dehumidification load during the entire year.

For our analysis, we will neglect the incremental cost or cost saving associated with the solar desiccant equipment. This incremental cost consists of two elements:

a) The incremental cost impact of replacing central electric or absorption chiller capacity with individual desiccant units. This element is unimportant here since if we consider a collector area of 150 ft^2/ton, (a reasonable approximation for actual sizing) a differential cost of \$100/ton of cooling would only amount to a cost of \$0.67/ft^2. This is only 6.7% of the total solar system cost if we assume a total system cost of \$10/ft^2.

b) The reduction in installed cost of the MIUS prime mover and generator. This factor could be important and should be considered in further studies.

4.4.5.2 Numerical Example

First the cost of the collected solar heat (SHC) can be calculated as:

$$SHC = \frac{R\ C/A}{\eta(Qi/A)}$$

Where the definitions and values of the parameters are as follows:

$\bar{\eta}$ is Annual Collection Efficiency = 40%

C/A is System Installed Cost = \$10/ft^2 (See Table 2.2.1)

(Qi/A)is Annual Insolation = 0.56×10^6 BTU/ft^2 YR

R is Amortization Rate - 0.10/YR

Therefore,

$$SHC = \frac{(0.1)\ (10)}{(0.4)\ (0.56 \times 10^6)} = 4.5\ \$/10^6\ BTU$$

Next, assuming a solar dehumidifier coefficient of performance (COP_s) of 0.5 the solar dehumidification

cost or solar cooling cost (SCC) expressed as dollars per unit "cold BTU" will be:

$$SCC = \frac{SHC}{COP_s} = \frac{4.5}{0.5} = \$9/10^6 \text{ BTU}$$

Finally, the 'break-even' cost of electricity resulting in the same cost of cooling will be the solar cooling cost multiplied by the coefficient of performance of the electric chiller. In this case, assuming an electric COP of 3.0, the 'break-even' electric cost would be $\$27/10^6$ BTU (7.9¢/KW-Hr). The break-even electric cost in this example is relatively high, and perhaps higher than the actual cost of MIUS power. Also, a portion of the displaced energy may be waste heat normally used to drive absorption machines. This will further degrade the economics of solar desiccant systems in MIUS. Substantial changes in the electric break-even cost can be influenced by:

- Reduced amortization (allowing a longer payback period.)
- Reduced annual system efficiency if the solar desiccant system were used only a few months a year.
- Allowing a cost benefit for a reduction in required electrical generation capacity.

Typical results for these variations from the original--or baseline situation are shown below.

Situation	Break-Even Electric Cost (¢/KW-HR)
Base-Line	7.9
Reduce Amortization Rate to 5%	3.95
Reduce Annual Efficiency to 20%	15.8
Reduce System Cost by 67% (By including $1000/ton cost benefit for installed capacity)	2.4

4.4.5.3 Preliminary Conclusions

Some conclusions relating to desiccant systems in MIUS can be summarized as follows:

a) The technology has tended to be a very specific and application-oriented art which is now undergoing a technology explosion in response to increased interest in solar energy and other energy conservation processes.

b) Designs evolving for solar space conditioning applications of desiccants may involve considerably different requirements, parameters, and configurations than those heretofore used. Therefore, the informational data base needs to be expanded.

c) The design, sizing, and economics of solar desiccant systems will be strongly dependent on climatic location and building type.

d) For larger buildings in MIUS which are centrally supplied with hot and chilled water, solar desiccant dehumidification might be cost competitive, depending on the cost benefits associated with reduction in electrical generation capacity.

e) Even if desiccant systems are not cost competitive in solar installations in MIUS, they may have advantages over absorption air conditioning that merit their use when activated by MIUS central hot water.

APPENDIX A

A.1 PARTITION OF ENERGY BETWEEN SOLAR CONTRIBUTION, WASTE-HEAT BOTTOMING CONTRIBUTION, AND PRIME MOVER CONTRIBUTION

The total electrical energy demand of MIUS W_M can be expressed as

$$W_M = W_D + W_R$$

Where, W_D is the diesel prime-mover contribution and W_R is the combined solar and waste-heat contribution. From the definition of thermal energy conversion efficiency

$$W_D = \eta_D Q_H \qquad (2)$$

and

$$W_R = \eta_R Q_I \qquad (3)$$

where, η_D and η_R are the diesel and Rankine-cycle efficiencies, Q_H is the heat added to the diesel engine, and Q_I is the heat added to the Rankine-cycle engine. By construction (see Figure A.1.1)

$$Q_I = Q_S + Q_r \qquad (4)$$

where Q_S is the useful collected solar energy added to the Rankine-cycle engine, and Q_r is the rejected heat from the diesel engine, which can be expressed as

$$Q_r = (1-\eta_D) \; Q_H \qquad (5)$$

Combining Eqs (1) to (5), yields

$$W_M = \eta_D Q_H + \eta_R \; (1-\eta_D) \; Q_H + \eta_R Q_S$$

or

$$Q_H = \frac{W_M - \eta_R Q_S}{\eta_D + \eta_R \; (1-\eta_D)} \qquad (6)$$

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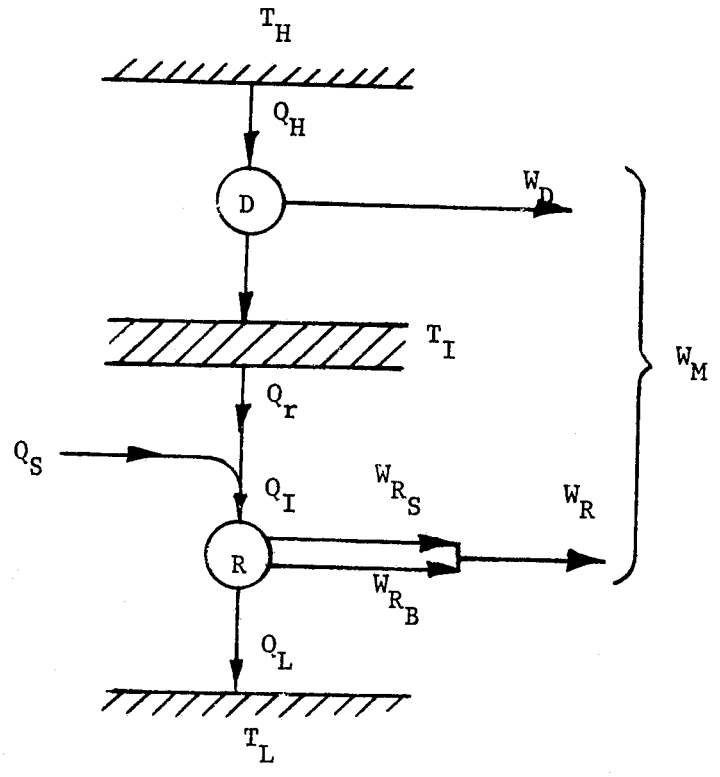


Figure A.1.1 Energy Interactions With Hybrid Solar and Waste-Heat Engines

From Eqs (2) and (3), Eq. (6) can be re-expressed as

$$\frac{W_D}{W_M} = \frac{1 - \frac{W_{R_S}}{(W_M)}}{1 + \eta_R\left(\frac{1}{\eta_D} - 1\right)} \qquad (7)$$

where W_{R_S} is the solar contribution from the hybrid Rankine-cycle engine. From Eq. (1),

$$\frac{W_D}{W_M} + \frac{W_{R_S}}{W_M} + \frac{W_{R_B}}{W_M} = 1$$

where W_{R_B} is the waste-heat bottoming contribution of the hybrid Rankine-cycle engine.

Assuming $\eta_R = 0.23$ and $\eta_D = 0.38$, we see that $W_D/W_M = 0.72$ when there is no solar contribution $\left(\text{i.e., } W_{R_S}/W_M = 0\right)$; whereas, at a 100% solar contribution, $W_D/W_M = 0$, as expected.

A.2 COMPUTER ANALYSIS OF SOLAR RANKINE-CYCLE ENGINE POWER GENERATION

Table A.2.1. displays a sample of the computer output for one month (December) of a full-year study of solar Rankine-cycle engine power generation. This annual study was repeated for various solar collector panel temperatures for determining the optimum system operating conditions. Table A.2.1 is for 350°F, the condition of maximum system solar energy conversion efficiency for advanced technology equipment utilized in the Washington, D.C. area. This table lists all of the primary solar collector and climatic input variables, as well as presenting an hourly, monthly, and annual summary of the system operating performance.

Table A.2.2 summarizes the solar collector panel and heat engine performance characteristics of the three case studies conducted for the Washington, D.C. area; Table A.2.3 presents an abbreviated listing of the results of these studies. Similar investigations were made for the Yuma, Arizona area, but are not reported here. Figure 4.1.7 does, however, present the results of the Yuma analyses.

A.3 BASIS OF COSTS OF ENERGY FROM SOLAR AND WASTE-HEAT BOTTOMING RANKINE-CYCLE POWER GENERATION

Table A.3.1 provides the cost bases for the economic evaluation of hybrid solar and waste-heat power generation for one of the cases considered in section 4.1. The costs in Table A.3.1 are for advanced technology equipment utilized in a power generation system which might operate in the Washington, D.C. area. Similar analyses were made for current technology equipment also operating in the Washington D.C. area. The results of this latter study were discussed in section 4.1.

WASHINGTON D.C. COOLING TOWER 4/30/75

LATITUDE = 38.6 DEG

NO. PANES	U	PANE SPACING	CONVECT. FACTOR	COLL. ABS.	COLL. EMISS.	GLASS ABS.	GLASS EMISS.	REFRACT. INDEX
1.	0.100	0.042	0.800	0.930	0.080	0.010	0.850	1.500

THE TEMPERATURE DROP ACROSS THE BOILER AND CONDENSER IS 10.0 DEG F

DATE	FIRST HOUR	MONTHLY DAYS	SUNSHINE FACTOR	DECLIN- ATION	WIND SPEED	C1	C2	AMB. TEMP	COLL. TEMP.	TILT ANG.	COLL. AZIMUTH	RIVER TEMP.	ENG. EFF.
DEC 21	8.	31.	0.47	-23.45	10.0	391.	0.142	41.	350.	38.6	0.0	36.0	0.239

HOUR	HOUR ANGLE (DEG)	SUN ALT. (DEG)	SUN AZIMUTH (DEG)	INCIDENT ANGLE (DEG)	NORMAL FLUX (BTU/HR)	COLL. FLUX (BTU/HR)	INCIDENT FRACTION	COLL. EFF.	SYS. EFF.	SYS. POWER (WATTS)
8.0	-60.0	6.3	-53.1	62.7	107.8	0.0	0.459	-0.828	-0.198	0.0
9.0	-45.0	15.0	-42.2	49.6	225.8	0.0	0.649	-0.026	-0.006	0.0
10.0	-30.0	21.9	-29.6	37.4	267.1	41.7	0.794	0.197	0.047	2.9
11.0	-15.0	26.4	-15.4	27.6	284.0	77.3	0.886	0.307	0.073	5.4
12.0	0.0	27.9	0.0	23.5	268.8	90.5	0.917	0.342	0.082	6.3
1.0	15.0	26.4	15.4	27.6	284.0	77.3	0.886	0.307	0.073	5.4
2.0	30.0	21.9	29.6	37.4	267.1	41.7	0.794	0.197	0.047	2.9
3.0	45.0	15.0	42.2	49.6	225.8	0.0	0.649	-0.026	-0.006	0.0
4.0	60.0	6.3	53.1	62.7	107.8	0.0	0.459	-0.828	-0.198	0.0

DAILY INCIDENT ENERGY FRACTION = 0.770
DAILY COLLECTION EFFICIENCY = 0.207
DAILY SYSTEM EFFICIENCY = 0.050

DAILY NORMAL ENERGY = 2058.3 BTU/H-FT2
DAILY INCIDENT ENERGY = 1584.6 BTU/H-FT2
DAILY COLLECTED ENERGY = 328.6 BTU/H-FT2
DAILY OUTPUT ENERGY = 23.013 WT-HR/FT2

MONTHLY NORMAL ENERGY = 29989.6 BTU/H-FT2
MONTHLY COLLECTED ENERGY = 4787.2 BTU/H-FT2

MONTHLY INCIDENT ENERGY = 23087.9 BTU/H-FT2
MONTHLY DELIVERED ENERGY = 335.30 WT-HR/FT2

ANNUAL NORMAL ENERGY = 497562. BTU/H-FT2
ANNUAL INCIDENT ENERGY FRACTION= 0.774

ANNUAL INCID. ENERGY = 384898. BTU/H-FT2
ANNUAL COLLECTION EFF.= 0.267

ANNUAL COLL. ENERGY = 102843. BTU/H-FT2
ANNUAL DELIVERED ENERGY = 6740.5 WT-HR/FT2

ANNUAL ENGINE EFFICIENCY = 0.2237
ANNUAL SYSTEM EFFICIENCY = 0.0598

Table A.2.1 Computer Output From Solar Power Generation Study

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TABLE A.2.2

SOLAR RANKINE ENGINE CASE STUDIES

The solar panel parameters are listed below for each case. The panel temperature will correspond to the condition of peak system efficiency (or, equivalently, peak delivered energy)

Solar Panel Parameters:

- Collector absorptivity: 0.93 all cases
- Collector emissivity: 0.08 all cases
- Glass absorptivity: 0.01 all cases
- Glass emissivity: 0.85 all cases
- One glass cover plate all cases
- Anti-reflective glass coating -- effective index of refraction = 1.35 cases I and I ; No coating n=1.5 Case III
- High vacuum cases I and II ; low vacuum Case III
- Heat loss coefficient: 0.05 BTU/hr-ft^2 -°F (evacuated fiberglas) Cases I and II, ; 0.1 case III

Heat Engine Parameters:

- $\eta_{Eng} = \epsilon \times \eta_{Carnot}$
- $\eta_{Carnot} = 1 - \frac{T_{refection} + 460}{T_{addition} + 460}$
- $T_{rejection} = T_{heat\ sink} + 10°\ F$
- $T_{addition} = T_{col} - 10°F$
- ϵ = 0.68 cases I and II; 0.65 case III

TABLE A.2.3

CASE I - WASHINGTON D.C. AREA - ADVANCED TECHNOLOGY

Given:

- $T_{col} = 350^{o}F$
- Collector Tilt Angle = 38.6^{o} (fixed)
- Latitude = 38.6^{o}
- Monthly mean ambient wet and dry bulb temperatures, wind speed, and percentage available sunshine taken from "Climatic Atlas of the U.S.", GSA Envir. Data Service, June, 1968
- Heat sink temperature = wet bulb temperature

Results:

- Average noontime (peak) delivered power = $12.3 w/ft^2$
- Annual delivered energy = 12.6 kw-hr/ft^2
- Annual collector efficiency, engine efficiency, and system efficiency = 47.5%, 23.4%, and 11.1%
- Land Impact:
  - -- average peak power = 3.7 acres/mw (peak)
  - -- annual delivered energy = 274 mw-hr/acre

CASE II - SAME AS CASE I EXCEPT FIXED REFLECTORS EMPLOYED

Given:

- Reflector reflectivity = 0.75
- Reflector extends from top of collector in one row to base of collector in next row
- Percentage improvements on attached sheet

Results:

- Avg. noontime (peak) delivered power = $15.5 w/ft^2$
- Annual delivered energy = 16.2 kw-hr/ft^2
- Land Impact:

-- average peak power = 3 acres/mw (peak)

-- annual delivered energy = 353 mw-hr/acre

TABLE A.2.3

CASE III - WASHINGTON, D.C. AREA - CURRENT TECHNOLOGY

Given:

- $T_{col} = 250^{o}F$
- Collector Tilt angle = 38.6^{o} (fixed)
- Latitude = 38.6^{o}
- Monthly ambient wet and dry bulb temps, wind speeds, and % available sunshine as per Case I
- Heat sink temp. = wet bulb temp

Results:

- Average noontime (peak) delivered power = 7.8 w/ft^2
- Annual delivered energy = 7.8 $kw-hr/ft^2$
- Annual coll. eff., eng, eff., and sys. eff. = 42.4%, 16.3%, and 6.9%
- Land Impact:

-- average peak power = 5.9 acres/mw (peak)

-- annual delivered energy = 170 mw-hr/acre

TABLE A.3.1

BASIS OF COSTS OF ENERGY FROM SOLAR-WASTE HEAT BOTTOMING RANKINE-CYCLE ENGINE CALCULATIONS BASED ON WASHINGTON, D.C. AREA CLIMATIC PERFORMANCE TECHNOLOGY EQUIPMENT

A. Solar Contribution to Annual MIUS Electrical Energy Demand:

- o Assume 5% contribution (6×10^6 mw-hrs)

B. Land, Energy, and Power Results:

- Land area - 17 acres (Fig 4.1.6 (a))
- Collector area = 370,000 ft^2 ($\sim$ 1/2 land area)
- Reflector area = 370,000 ft^2 ($\sim$ collector area)
- $W_{r_B}/W_m = 0.26$; $W_d/Wm = 0.69$ (Fig. 4.1.2)
- Annual rankine-engine energy contribution =

  $(0.26 + 0.05) \times (120 \times 10^6$ kw-hrs)

  $(31.2 + 6) \times 10^6$ kw-hrs = 37.2×10^6 kw-hrs
- Average peak solar rankine-engine power = 5.7 mw (Fig. 4.1.6 (a))
- Waste-heat rankine-engine power at solar peak* = 0.21 25mw = 5.3mw
- Total noontime rankine-engine power = 5.7 + 5.3 = 11mw
- Waste-heat rankine-engine power at 7:00 p.m.

  (Max. MIUS demand, zero solar contribution) =

  0.28 x 31.5 mw = 8.7 mw (Fig. 4.1.2)
- Thus, combined rankine engine must be sized for 11mw noontime load
- Peak rankine engine reject heat =

  $[(1-\eta_R)/\eta_R] \times W_{R_{tot}} =$

  [(1-0.23)/0.23] x 11mw = 36.8mw = 10,500 tons

C. Solar Collection Subsystem Installed Costs:

- Collectors = \$11/ft^2 (Table 2.2.1)
- Reflectors (1) = \$0.75/ft^2
- Collector & Reflector supports (1) = 2 x \$0.40/ft^2
- Piping, valves, insulation, controls, misc. fittings (1) = \$0.30/ft^2

*At noontime: W_{r_s}/Wm = 5.7mw/25mw = 0.23. From Fig 4.1.2, W_{r_b}/Wm = 0.21

TABLE A.3.1 Continued

- Anti-freeze heat transfer liquid [2] = $0.25/ft^2
- Land purchase = $o/ft^2
- Total cost = ($13.1/ft^2) x (370,000 ft^2) = $4.85 x 10^6

D. Rankine-Cycle Engine Installed Costs:

- Waste-heat recovery heat exhanger
- Pressurized water-to-organic working fluid heat exchanger
- Condenser
- Regenerator
- Turbine
- Feed Pump
- Gear Reducer
- Piping, insulation, structural supports, misc.
- Alternator
- Switch gear
- Transmission lines
- Instrumentation and controls
- Total cost[3] = ($250/kw) x (11,000 kw) = $2.75 x 10^6

E. Cooling Tower Installed Costs:

- Cooling Tower
- Controls
- Piping
- Misc.
- Total cost [2] = ($35/ton) x (10,500 tons) = $ 0.37 x10^6

Data Resources:

(1) ADL Phase II report, "A Design Study to Determine the Technical Economic Feasibility of a Solar Water Pumping System for the Welton-Mohawk Desalination Plant", prepared for the Office of Water Research and Technology, Department of Interior, Dec. 1974.

(2) Estimate prepared from ADL's Solar Climate Control Project Data Base

(3) Barber, R.E., "Rankine-Cycle Systems for Waste Heat Recovery" Chemical Engineering, pp. 101-106, Nov. 25, 1974.

APPENDIX B

COMPUTATION OF STRAIGHT PAYBACK PERIOD (SPP) FOR A SOLAR WATER PREHEATING SYSTEM

Table B.1 illustrates the methodology for using the performance curves to calculate the payback period. Selecting a value for the ratio of annual incident solar flux to the annual load, Qi/load, and using the value of annual flux incident on the collector, 0.56×10^6 BTU/ft^2-yr, the performance curve yields a value for the percentage of the load met by the solar system, %S, for a given size system as measured by the collector area. From the relationships given in Table 3.4.4 the system annual efficiency is determined and the quantity of solar energy collected and used to displace the electric hot water heating is calculated. The operating costs for the solar system consist of the auxiliary energy expenditure to supply the fraction of the load not satisfied by the solar system and the electrical power dissipation in the solar collector loop pump. As a general rule of thumb, a properly designed system might require about 2 kwh of pump energy for every million BTU's of solar heat collected. The system capital costs are related to the size of the systems as measured by the collector area (see Section 2.2). From the capital costs and the operating cost savings, the straight payback period (SPP) is then determined.

TABLE B.1

Solar Water Heating

- Annual flux: 0.56×10^6 Btu/ft^2 - yr
- Select collector area, A
  - → Qi/load
  - → % Solar, from performance curves
  - → $\overline{\eta}$, system efficiency
  - → solar energy collected and used
- Solar collector loop pump: $\approx$ 2 kwh/10^6 Btu collected
- Calculate auxiliary energy expenditure
- From collector area, find system capital cost
- Calculate SPP