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CONSIDERATIONS FOR PERFORMANCE EVALUATION OF SOLAR HEATING AND COOLING SYSTEMS

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16. ABSTRACT

One of the many factors which must be considered in performance evaluation of solar energy systems is the relative merit of a given solar energy system when compared to a standard conventional system. Although initial and operational costs will be dominant factors in the comparison of the two types of systems and will be given prime consideration in system selection, sufficient data are not yet available for a definitive treatment of these variables. It is possible, however, to formulate relationships between the nonsolar energy requirements of the solar energy systems and the energy requirements of a conventional system in terms of the primary performance parameters of the systems. This report presents derivations of such relationships, provides some parametric data for selected ranges of the performance parameters, and examines the data with respect to limiting conditions.

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LIST OF SYMBOLS

Symbol	Definition
COP_a	Coefficient of performance of auxiliary energy subsystem
COP_c	Coefficient of performance of conventional system
COP_s	Solar energy system coefficient of performance
E_a	Portion of heating or cooling load satisfied by auxiliary energy subsystem
E_c	Energy required to accommodate a given heating or cooling load for a conventional system
E_{col}	Rate of energy collection by solar collectors
E_{cr}	Resource energy requirement, conventional system
E_{csr}	Resource energy requirement, solar energy system
E_e	Energy required for pumps and fans, solar energy system
E_g	Energy provided by the Rankine cycle
E_L	Heating or cooling load
E_R	Energy required to drive the Rankine cycle
E_s	Portion of the heating or cooling load satisfied by the solar energy system
δ_e	Difference between energy requirements of conventional and solar energy systems
δ_{er}	Difference between resource energy requirements of conventional and solar energy systems
η_a	Ratio of E_R/E_L

LIST OF SYMBOLS (Concluded)

Symbol	Definition
η_c	Efficiency of energy delivery process, conventional system
η_{cs}	Efficiency of energy delivery process for E_a
η_{cse}	Efficiency of energy deliver process for E_e
η_R	Rankine cycle efficiency
η_s	Percentage of heating or cooling load provided by solar energy system
η_u	Solar energy utilization efficiency

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CONSIDERATIONS FOR PERFORMANCE EVALUATION OF SOLAR HEATING AND COOLING SYSTEMS

INTRODUCTION

The first test of the potential for a solar heating and cooling system to reduce the demand on fuel supplies is for the system to use less conventional energy than a comparable conventional system. Cost, both first and operational, will be a major factor in achieving widespread application, which is also necessary to reduce the demand on fuel supplies.

Although it is difficult to define criteria that adequately treat cost variables due to the immature state of the market and industry, the ability of a solar energy system to conserve conventional energy can be determined. An approach for this determination is presented in this report.

ENERGY SAVINGS DETERMINATION

The ability of a given solar energy system to reduce the demand on present fuel supplies may be determined by establishing the savings that can be achieved by comparison with the conventional heating and/or cooling system that would normally be used for the intended application. A relationship must be established between the solar energy system and the conventional system that relates the difference in conventional energy requirements of the systems to their performance parameters.

The following development and the resulting relationship are valid for a solar energy system in which the solar energy is used directly from the collector or storage device for heating and cooling (i.e., is not used to assist a heat pump).

First, considering a conventional system, the energy, E_c, required to accommodate a given heating or cooling load, E_L, can be expressed in terms of the load and the coefficient of performance of the system, COP_c, as

$$E_c = \frac{E_L}{COP_c} \quad . \tag{1}$$

If one also accounts for the efficiency of the process required to deliver the energy to the heating or cooling system, η_c, a "resource" energy requirement, E_{cr}, can be written as

$$E_{cr} = \frac{E_L}{\eta_c(COP_c)} \quad . \tag{2}$$

The efficiency, η_c, should include all energy expended to deliver the required energy to the system but, for the purposes of comparing conventional and solar energy systems, can be determined based on a common point of origin for the two applications.

Similarly, for a solar energy system, the nonsolar energy required to satisfy the heating or cooling load can be expressed in terms of the portion of the load satisfied by the auxiliary energy subsystem, E_a, the coefficient of performance of the auxiliary energy subsystem, COP_a, and the energy required for pumps, fans, etc., E_e. The auxiliary energy subsystem includes the device for adding energy and the heating or cooling device.

$$E_{cs} = \frac{E_a}{COP_a} + E_e \quad . \tag{3}$$

In this relationship, E_e is the actual energy required and includes the inefficiencies of the devices used. Allowing again for the efficiencies of the energy delivery processes, a resource energy requirement can be written as

$$E_{csr} = \frac{E_a}{\eta_{cs}(COP_a)} + \frac{E_e}{\eta_{cse}} \quad . \tag{4}$$

It will be noted that, to provide a general relationship, different subscripts have been used for the energy delivery efficiencies for the conventional system, the auxiliary energy subsystem, and for the pumps, fans, etc., utilized in the solar energy system.

The difference between the nonsolar energy requirements of the conventional and solar energy systems, δ_e, can be obtained by subtracting equations (1) and (3):

$$\delta_e = \frac{E_L}{COP_c} - \frac{E_a}{COP_a} - E_e \quad . \tag{5}$$

A more general expression that allows one to evaluate the difference in resource energy requirements, δ_{er}, can be obtained by subtracting equations (2) and (4):

$$\delta_{er} = \frac{E_L}{(COP_c)\eta_c} - \frac{E_a}{\eta_{cs}(COP_a)} - \frac{E_e}{\eta_{csc}} \quad . \tag{6}$$

Since the auxiliary energy requirement is simply the difference between the heating and/or cooling load and the portion of the load provided by the solar energy system, E_s, equation (6) can be rewritten as

$$\delta_{er} = \frac{E_L}{(COP_c)\eta_c} - \frac{(E_L - E_s)}{\eta_{cs}(COP_a)} - \frac{E_e}{\eta_{csc}} \quad . \tag{7}$$

This equation is valid for the specific case in which the auxiliary energy subsystem and the solar energy subsystem for heating or cooling are operated at the same COP. Defining the percentage of heating and/or cooling load provided by the solar system as

$$\eta_s \equiv \frac{E_s}{E_L} \quad ,$$

equation (7) can be rewritten as,

$$\frac{\delta_{er}}{E_L} = \frac{1}{(COP_c)\eta_c} - \frac{(1-\eta_s)}{\eta_{cs}(COP_a)} - \frac{E_c}{\eta_{cse}(E_L)} \quad . \tag{8}$$

It is obvious that a viable solar energy system must require less non-solar energy for its operation than a comparable conventional system. In fact, to be economically viable, it must operate on considerably less conventional energy, so that energy savings over its operational life will compensate for the characteristically higher cost of the solar energy systems. However, it is informative to first investigate the variables in equation (8) in terms of a "break-even" situation, $\delta_{er}/E_L = 0$. To further simplify the situation, it will be assumed that the conventional and solar energy systems employ the same non-solar energy resource (e.g., let both the conventional system and the auxiliary energy device for the solar energy system utilize electricity) so that $\eta_c = \eta_{cs} = \eta_{cse}$. For the break-even situation then,

$$\frac{1}{COP_c} - \left(\frac{1-\eta_s}{COP_a} + \frac{E_c}{E_L} \right) = 0 \quad , \tag{9}$$

and the required percentage of solar energy can be expressed as

$$\eta_s = 1 + COP_a \left(\frac{E_c}{E_L} \right) - \frac{COP_a}{COP_c} \quad . \tag{10}$$

Parametric data for selected ranges of the variables appearing in equation (10) are provided in Figures 1 and 2. The data indicate that the penalties imposed on a solar energy system that incorporates an auxiliary energy device with a low coefficient of performance are severe and that the energy requirements imposed by other energy consumers such as fans and pumps, which would not be

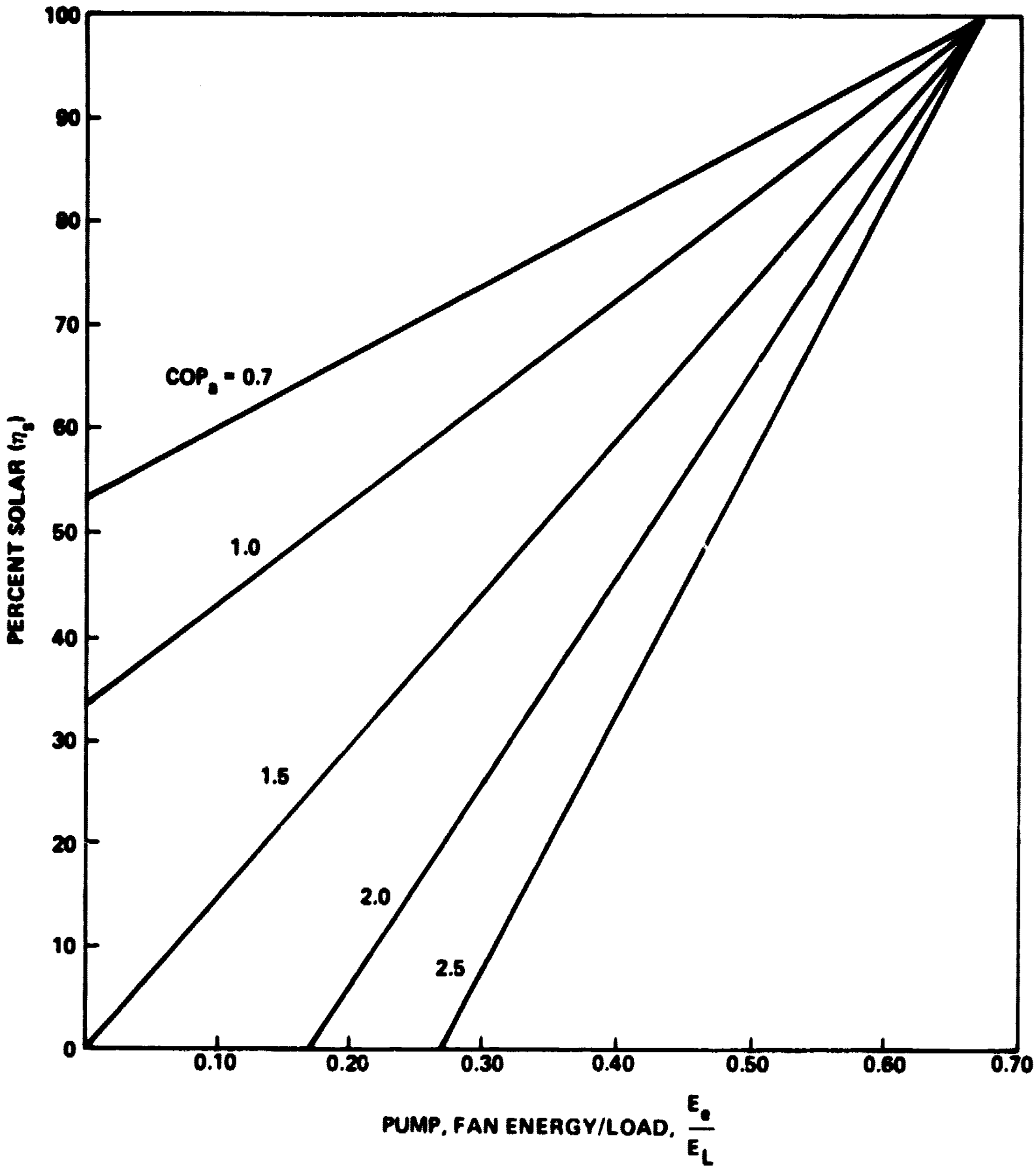

Figure 1. Solar energy required to break even, $COP_c = 1.5$.

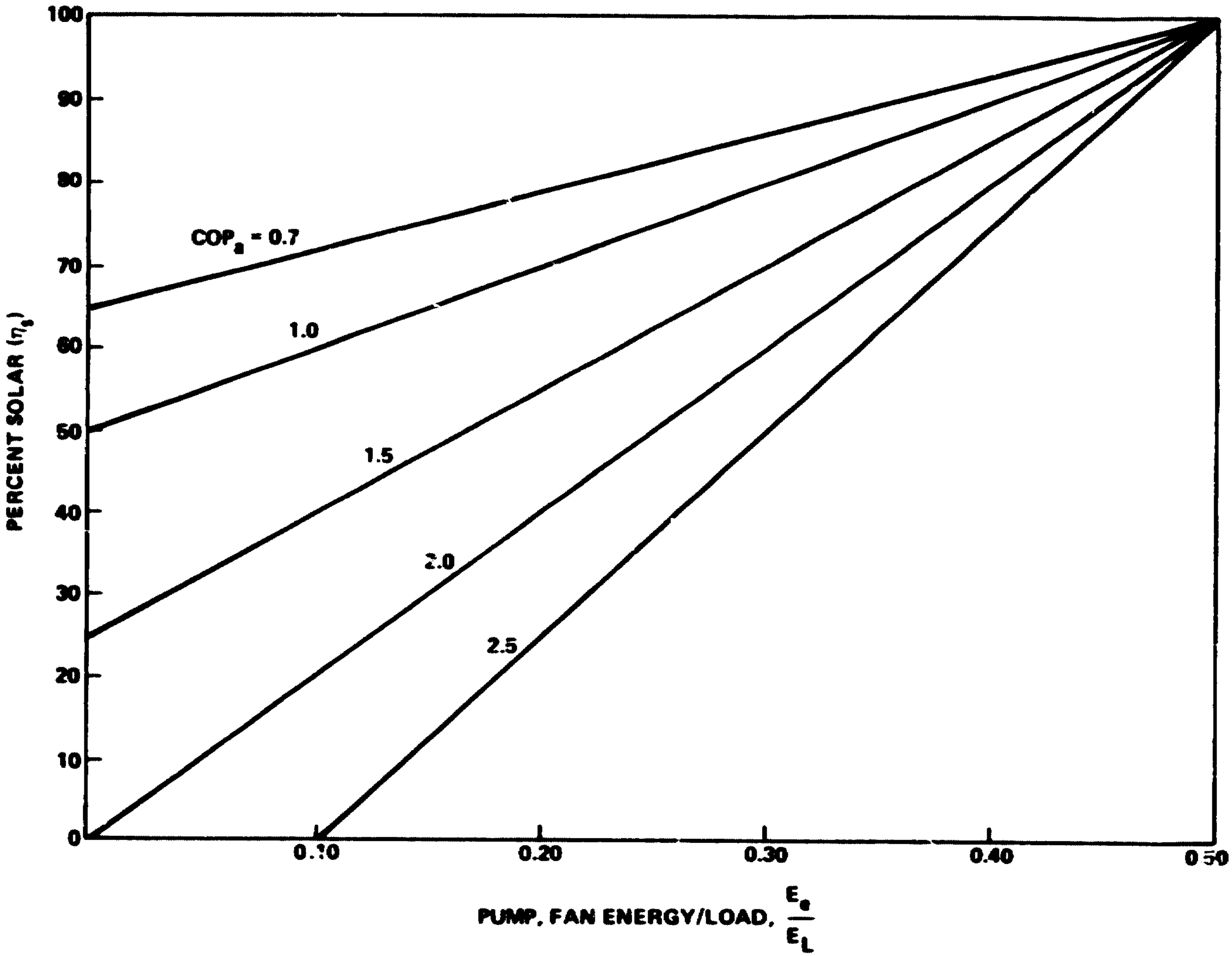

Figure 2. Solar energy required to break even, $COP_c = 2.0$.

present in the conventional system, serve to increase the penalties significantly. An examination of Figure 2 reveals that more than 50 percent of the required load must be supplied by solar energy to break even if a conventional system with a coefficient of performance of 2.0 could have been selected rather than the solar energy system and if the solar energy system has an auxiliary energy device with a coefficient of performance of 1.0 or less. If any significant amount of energy is required for pumps and fans, the COP of the solar energy system's auxiliary energy device must be somewhat greater than 1.0 for a break-even situation to be achieved when 50 percent of the load is supplied by solar energy.

Two informative limiting cases for equation (10) can also be examined. Consider first the ideal case in which no conventional power is required by the solar system for pumps, fans, etc. For this case,

$$\frac{E_e}{E_L} = 0$$

and

$$\eta_s = 1 - \frac{COP_a}{COP_c} \quad . \tag{11}$$

In this instance, the break-even solar energy is a function of the coefficient of performance of the auxiliary energy device for the solar system and the coefficient of performance of the conventional system selected for comparison. Parametric data for a range of the pertinent variables of equation (11) are provided in Figure 3. Again, the need for comparable COP's for the solar energy system's auxiliary energy device and the conventional system that could have been chosen is apparent.

Next, consider the case in which the solar system provides 100 percent of the heating and/or cooling load. Then, from equation (10),

$$\frac{E_e}{E_L} = \frac{1}{COP_c} \quad . \tag{12}$$

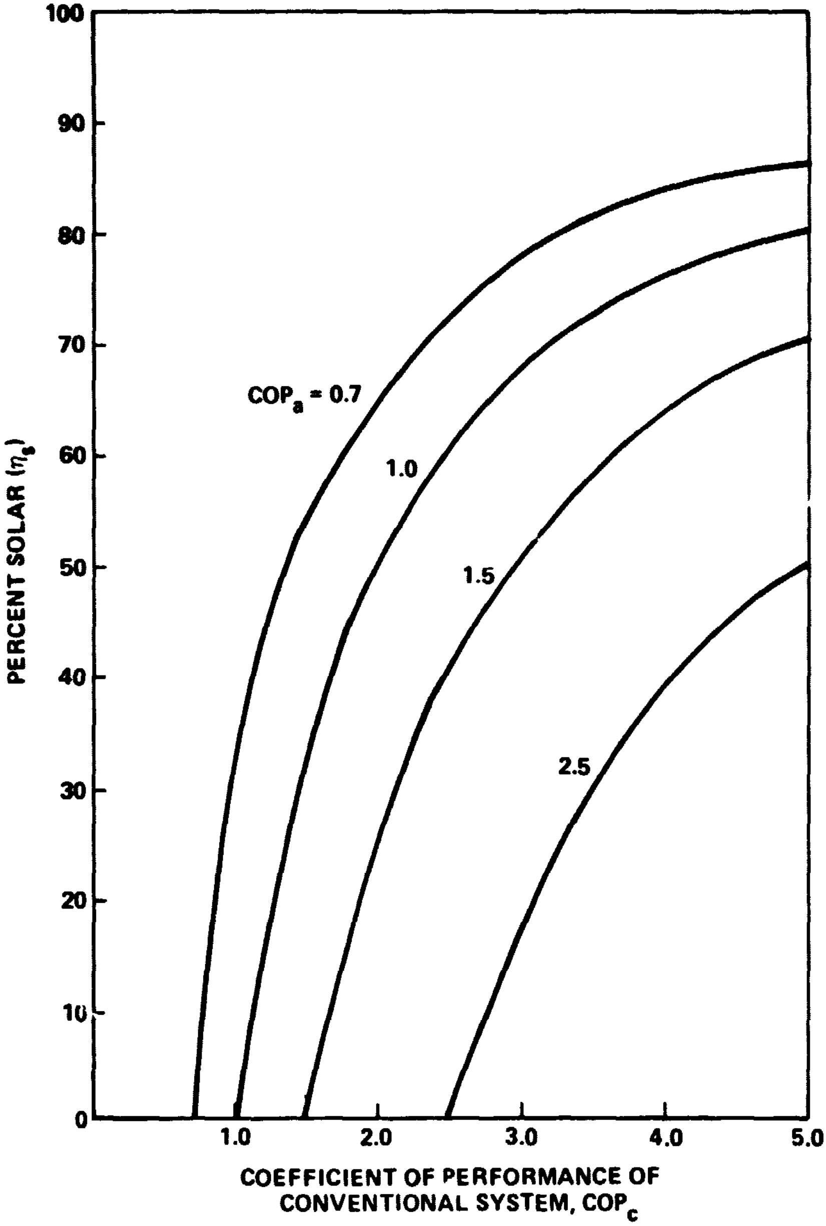

Figure 3. Solar energy required to break even, $E_c/E_L = 0$.

This defines the theoretical upper limit for conventional energy to operate pumps, fans, etc., as a function of the "standard" conventional system coefficient of performance. It should be observed that, for this condition, the allowable energy foı pumps, fans, etc., in the solar energy system is indpendent of the coefficient of performance of the auxiliary energy device, since all of the heating and/or cooling load is provided by solar energy. While the limiting cases defined by equations (11) and (12) are interesting, it must be emphasized that for real systems which provide less than 100 percent solar energy and have positive energy requirements for fans, pumps, etc., the break-even requirements are significantly greater than reflected.

It has been demonstrated that the coefficient of performance of the solar energy system auxiliary energy device is extremely important. The type of fuel required to operate the device as compared to the type of fuel required by the standard conventional system also influences the break-even point for energy conservation. Although the selection of a fuel source must be influenced by many factors, including the future availability of the selected fuel, the effect of the selection on the goal of reducing the demand on present fuel supplies should be considered. The relationship needed can be obtained from a rearrangement of equation (8) together with the assumption that the conventional energy system and the pumps and fans in the solar system are operated by the same energy source, $\eta_{cse} = \eta_c$. Setting $\delta_{cr} = 0$,

$$\eta_s = 1 + \frac{\eta_{cs}}{\eta_c}\left[\frac{E_c(COP_a)}{E_L} - \frac{COP_a}{COP_c}\right] \quad . \tag{13}$$

In generating the data provided in Figures 1 and 2, the assumption was made that the conventional system and all components in the solar energy system utilized electricity. Let us reexamine the data based on an auxiliary energy device that utilizes gas and has an efficiency, η_{cs}, of 60 percent. The comparison will be made with a conventional energy system that utilizes electricity, and pumps and fans in the solar energy system that also utilize electricity. It will be assumed that the efficiency of the power generation plant and transmission system is 30 percent. Using these assumptions and choosing a conventional system coefficient of performance of 2.0 as a basis of comparison, the data of Figure 4 were generated. A comparison of these data with Figure 2 (in which the solar energy system auxiliary energy device utilized electricity and $\eta_{cs}/\eta_c =$ 1.0) illustrates the effect of fuel selection. It is seen that, for the assumptions previously outlined, the break-even energy requirement is reduced significantly.

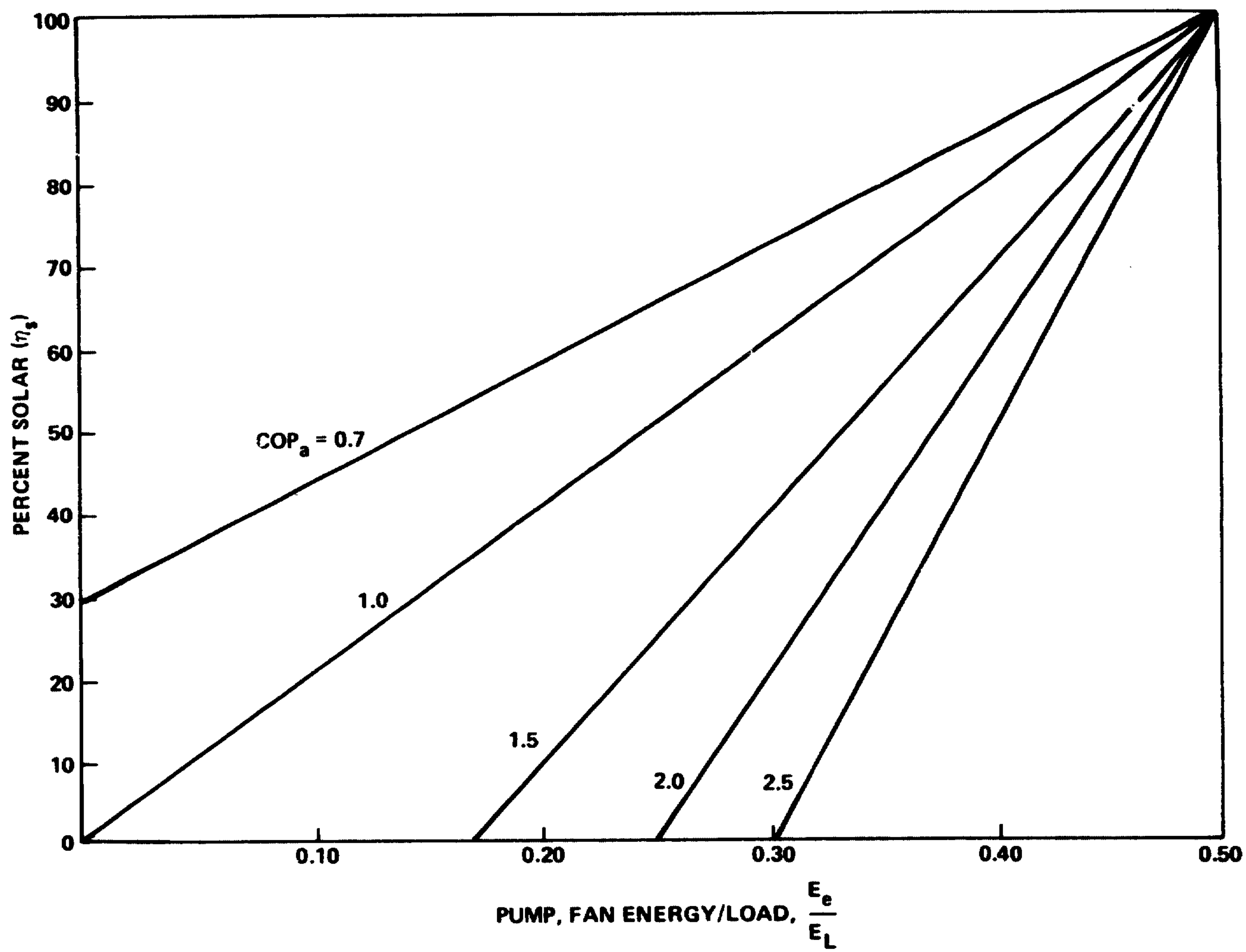

Figure 4. Solar energy required to break even, $COP_c = 2.0$, $\eta_{cs}/\eta_c = 2.0$.

SOLAR DRIVEN RANKINE COOLING DEVICE

Although equation (10) is applicable to the solar driven Rankine cooling device, it is informative to relate the percentage of the load supplied by solar energy to the energy required to drive the Rankine cycle.

The energy that the Rankine cycle must supply to the auxiliary subsystem or cooling device is

$$E_g = \frac{\eta_s E_L}{COP_a} \quad . \tag{14}$$

The solar energy into the Rankine cycle is found by

$$E_R = \frac{E_g}{\eta_R} \quad . \tag{15}$$

Combining equations (14) and (15) and solving for η_s gives

$$\eta_s = COP_a \frac{E_R}{E_L} \eta_R \quad . \tag{16}$$

By defining the ratio of solar energy required by the Rankine cycle to load requirements as

$$\eta_a = \frac{E_R}{E_L} \quad , \tag{17}$$

equation (16) becomes

$$\eta_s = \eta_R \eta_a \, COP_a \quad . \tag{18}$$

Equation (18) expresses the percentage of the load provided by solar energy, η_s, as a function of the ratio of the solar energy required to drive the Rankine cycle and the cooling load, η_a, and the product of the Rankine cycle efficiency and cooling device coefficient of performance. Figure 5 presents parametric data generated from equation (18). Since η_a will be a strong driver in sizing the solar collector and storage device, the relationship of η_a with the percentage of the load to be supplied by solar energy and the system performance parameters is an important design consideration.

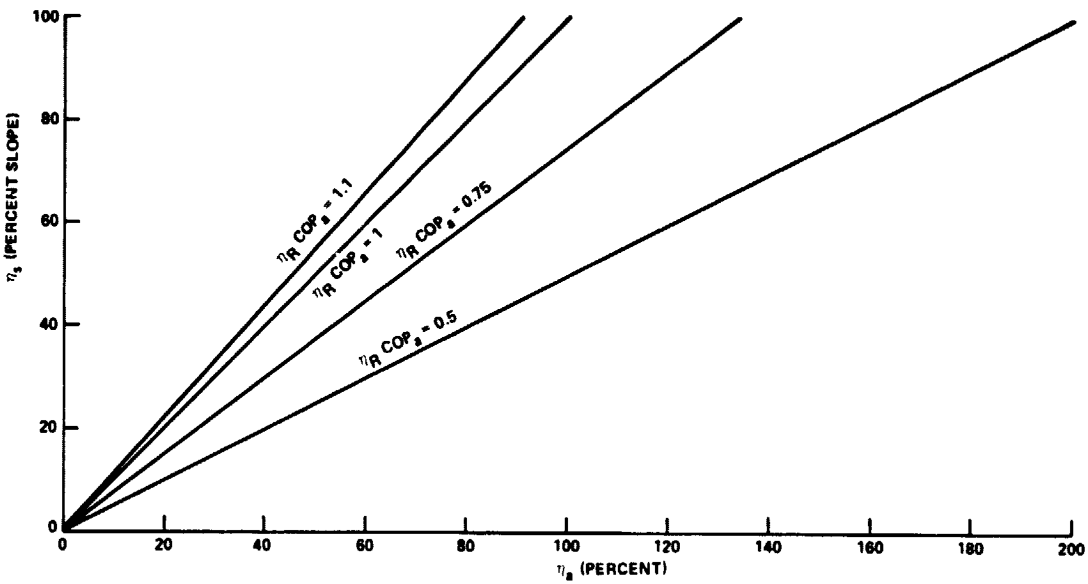

Figure 5. Solar energy required to break even as a function of η_a, η_R, and COP_a.

Assuming that the auxiliary device COP_a and COP_c of the conventional device are equal, equation (10) can be reduced to

$$\eta_s = COP_a \frac{E_e}{E_L} \quad . \tag{19}$$

the assumption of equal coefficient of performance is reasonable since a viable Rankine system must have a cooling device with a high coefficient of performance and since it can be operated entirely on auxiliary energy, it could be used as a conventional cooling device.

Figure 6 presents parametric data generated from equation (19). The data in Figure 6 show the allowable E_e / E_L increasing as the coefficient of performance decreases for a given η_s, which may appear to be a contradiction. This occurs because we are still comparing the auxiliary COP_a and the conventional COP_c although the auxiliary COP_a and conventional COP_c have been set equal [equation (18)], and as the coefficient of performance increases, less electrical energy can be used to drive equipment and still maint: in a break-even point. This can be further demonstrated by rearranging equation (10) and finding the limit on E_R / E_L as $COP_a = COP_c$ approaches infinity,

$$\lim_{COP \to \infty} \left(\frac{\eta_s - 1}{COP_a} + \frac{1}{COP_c} \right) = 0 \quad . \tag{20}$$

This is an important consideration because as coefficents of performance of systems are improved, improvements in collector loop pumps, fans, etc., must also be made.

Using Figures 5 and 6 one can evaluate a Rankine system break-even condition for a given set of efficiencies, coefficient of performance, and electrical energy usage. In using the data in this report, one must realize that all the parameters must be averaged over a reasonable cooling and/or heating operating period.

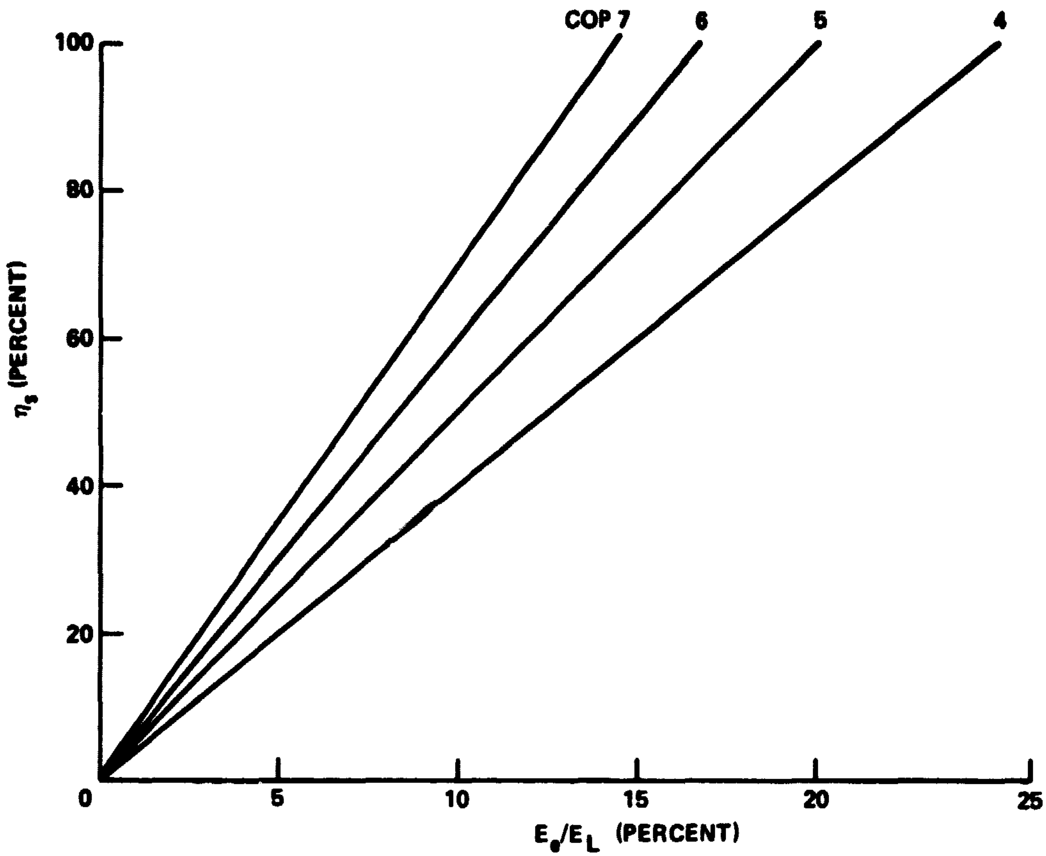

Figure 6. Solar energy required to break even, $COP_a = COP_c$.

CONCLUSIONS

A technique has been developed for comparing solar heating and/or cooling devices with conventional heating and/or cooling devices to determine if conventional energy can be saved. The technique outlined is applicable to systems using solar energy directly to drive a cooling or heating device and to systems using solar energy to drive a Rankine cycle which in turn drives a cooling device.

Although the technique is limited to these system configurations, it could be developed further to include such systems as the solar assisted heat pump.

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APPROVAL

CONSIDERATIONS FOR PERFORMANCE EVALUATION OF SOLAR HEATING AND COOLING SYSTEMS

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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