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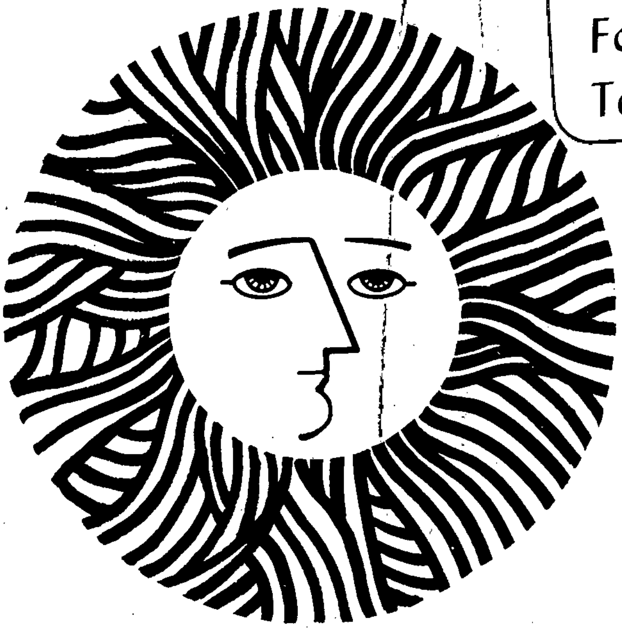

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Cost and Performance Goals for Commercial Active Solar Absorption Cooling Systems.*

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ABSTRACT

Economic and thermal performance analysis is used to determine cost goals for typical commercial active solar cooling systems to be installed between the years 1986 and 2000. Market penetration for heating, ventilating, and air conditioning systems depends on payback period, which is related to the expected return on investment. Postulating a market share for solar cooling systems increasing to 20 % by the year 2000, payback and return on investment goals as a function of year of purchase are established. The incremental solar system cost goal must be equal to or less than the 20 year present value of future energy savings, based on thermal performance analysis, at the desired return on investment. The methodology is applied to determine the allowable incremental solar system cost for commercial-scale, 25 ton absorption cooling systems based on the thermal performance predicted by recent simulation analysis. Methods for achieving these cost goals and expected solar cooling system costs will be discussed.

INTRODUCTION

The attainment of reasonable market penetration of active solar cooling systems, beginning with introduction of commercial units in the late 1980's and continuing through the 1990's, can be related to meeting certain cost goals for these systems.[1,2] A solar cooling or cooling/heating system is taken to be cost-effective when the incremental solar system cost is equal to (or less than) the present value of the energy savings. The present value over the life of the system (20 years) of the fuel saved by an active solar system has been calculated and is a function of the fuel escalation rates and the expected real return on investment. The real return on investment is the return over and above the general inflation rate.

The economic performance requirement for a solar system can be expressed in terms of payback period, the number of years for the undiscounted system savings to equal the incremental cost of the solar system over that of a conventional system providing the same service. A market assessment performed by OR/MS Dialogue [3] has developed a relationship between payback period and market acceptance of a product. If payback period is shorter, that product is more acceptable. Based on their assessment, significant market penetration (20%) would be achieved with a payback period of about 9 years. The payback period is closely related to the real return on investment which is dependent on the assumed rates for general inflation and fuel escalation.

Economic performance goals for active space conditioning systems developed previously[1,2] are shown in Table 1. To achieve a 20 % market penetration by the year 2000, an 8.9 year payback or a real return on investment of 11.4% is required. With assumptions regarding the price of fuel, fuel escalation rate, and general inflation rate, the incremental investment for saving 1 GJ/yr (1.054 x 10^6 Btu/yr) of electricity or natural gas for representative systems in Phoenix have been determined and are also shown in Table 1.

Table 1. Economic Performance Goals and Representative System Incremental Investment Goals for Phoenix (as developed in reference 2).

YEAR 2000 System Economic Performance Goals

Market Penetration	20%
Real Return on Investment (ROI)	11.4%
Payback Period	8.9 yr
Investment Goal/ GJ_g/yr Natural Gas Saved	$85
Investment Goal/ GJ_e/yr Electricity Saved	$340
Investment Goal/ First Year Cost Savings	~10.

Postulating commercial introduction of solar cooling systems in 1986 with the market share increasing to 20 % by the year 2000, payback and return on investment goals for cooling systems as a function of year of purchase can be established. Preliminary cost goals for systems to be installed between the years 1986 and 2000 have been determined using economic and thermal performance analyses of typical residential and commercial active solar cooling systems [1,2]. Using the results of previous systems analysis [4,5] of representative 25 ton commercial solar Rankine and absorption cooling systems, the incremental solar system cost goals were calculated for three cities (Ft Worth, Phoenix, and Miami) as shown in Figure 1. These results are, however, quite sensitive to the energy savings predicted by the simulation analysis.

SIMULATION ANALYSIS

A more recent study [6] includes a careful analysis of the thermal performance and parasitic power consumption of commercial 25 ton absorption and Rankine cooling/heating systems. Annual system simulations of the thermal performance of active solar Rankine and absorption cooling/heating systems have been conducted by SAI using TRNSYS. These calculations have been carried out for commercial solar cooling/heating systems in four cities (Fort Worth, Phoenix, Miami, and Washington, D.C.) that are representative of the cooling market. Three types of systems have been evaluated: commercial 25 ton absorption (ARKLA), and commercial 25 ton Rankine (Honeywell) at 195 °F and 300 °F generator temperatures. For this paper we shall limit our analysis to the 25 ton absorption cooling system.

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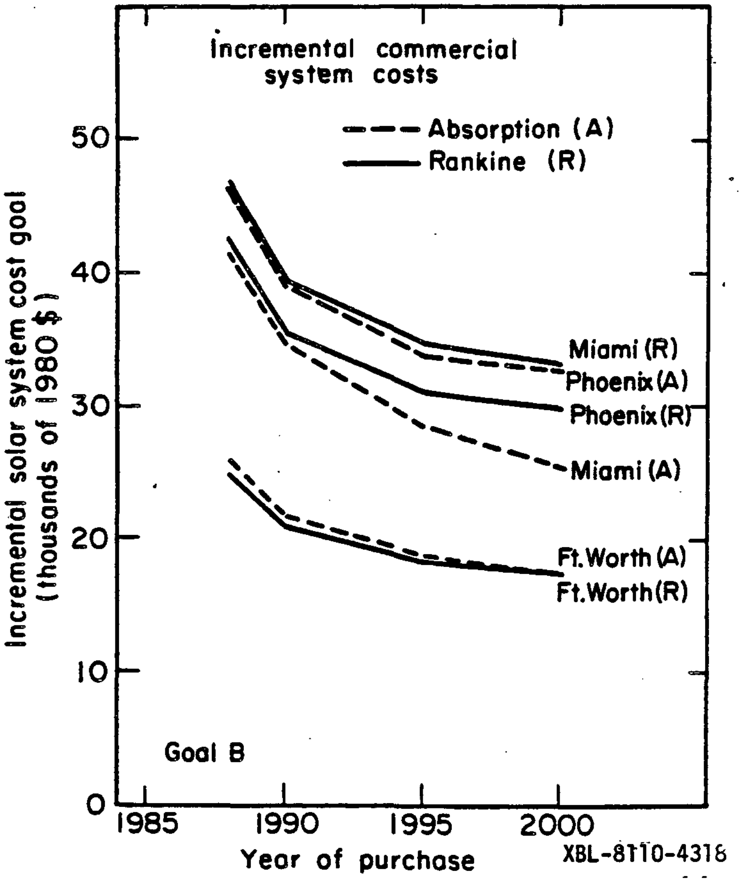

Figure 1. Preliminary commercial Rankine and absorption incremental solar system cost goals for representative 25 ton systems in three cities to achieve a 20 % market penetration in the year 2000 (from reference 2).

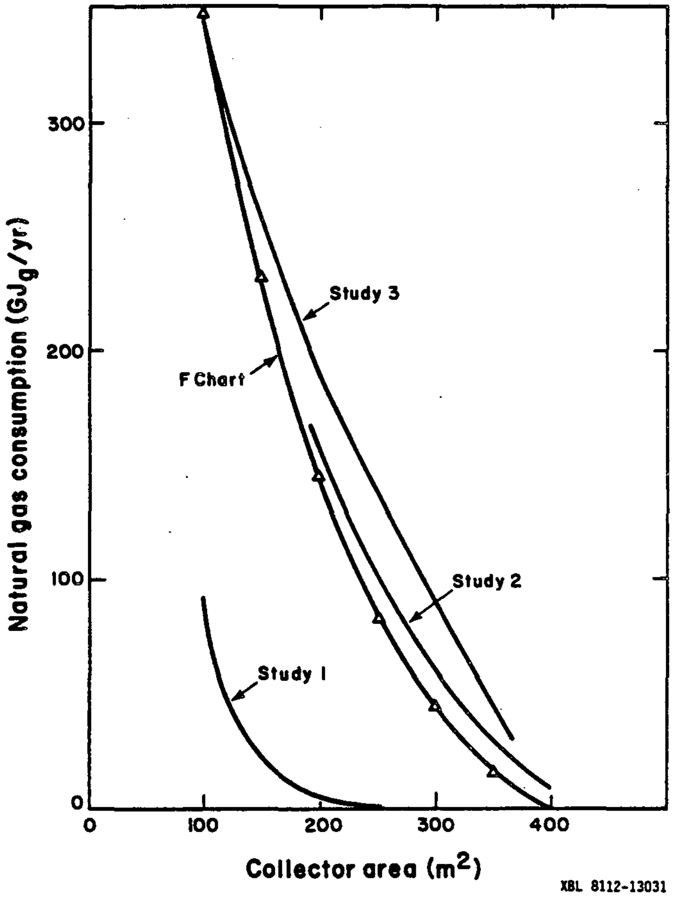

Figure 2. Natural gas consumption (GJ_g/yr) for a 25 ton solar absorption cooling system in Phoenix as a function of collector area, from three different studies.

The commercial buildings used in the analysis were taken from the document "Standard Assumptions and Methods for Solar Heating and Cooling Systems Analyses." [7] The small well-constructed seven-zone office building used in the analysis has a nominal design cooling load of 25 tons and meets or exceeds ASHRAE 90-75 standards. Additional energy conservation features such as low total lighting levels and minimum ventilation rate are incorporated. The building was originally described for Washington, DC; however, the description is adequate in other geographic locations if the gross air circulation value is changed for each location. Hourly building load calculations were based on a DOE2.1 simulation analysis. Hourly commercial chiller loads are used to drive the TRNSYS system performance simulation.

The keys to cost effective active solar space conditioning systems are energy savings and system installation costs. The new simulations predict somewhat less energy savings than earlier analyses. Figure 2 shows the natural gas consumption of a solar absorption air conditioning system in Phoenix for different collector areas, as predicted from three different studies. The parasitic electrical energy consumption is shown in Figure 3.

Study 1 [4] was a preliminary study with an oversimplified computer model of the absorption chiller. It has the lowest prediction for energy consumption to satisfy a given cooling load. The results of Study 1 were used to establish the preliminary cost/performance goals for commercial absorption systems shown in Figure 1. Study 2 [5] used an improved chiller model to valuate different storage options. The parasitic power predicted in the simulation is considerably less than that of Study 1, as shown in Figure 3. Study 3 [6], the most recent analysis, carefully analyzes both the chiller and the system electrical energy consumption. It predicts slightly higher natural gas consumption than the two earlier studies, but more importantly predicts considerably higher parasitic power consumption. Also shown on Figure 3 are the electrical energy requirements for a conventional vapor compression air conditioner in Studies 1 and 2 that assumed an electrical coefficient of performance, ECOP, of 3.0 GJ_{th}/GJ_e (Btu_{th}/Btu_e) for an annual cooling load of 398 GJ/yr(378 MBtu/yr), as well as that for Study 3 which assumed an ECOP of 4.0 GJ_{th}/GJ_e (Btu_{th}/Btu_e) and recalculated the cooling load at 363 GJ/yr(344 MBtu/yr).

To check the validity of the larger natural gas usage predicted by Study 3, FCHART 4.0 analysis was performed assuming that the active cooling system can be modeled as an industrial process application with a minimum useful storage temperature of 71.1 °C (160 °F) to drive the chiller to meet the total cooling load. The energy delivered to the process from the collector

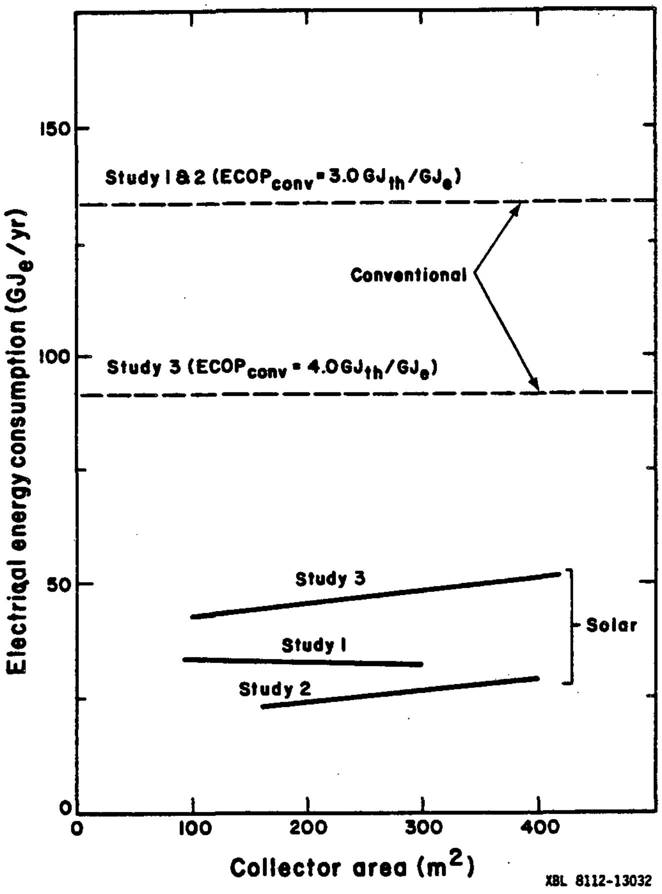

Figure 3. Electrical energy consumption (GJ_e/yr) for a 25 ton solar absorption cooling system with natural gas backup in Phoenix as a function of collector area, from three different studies.

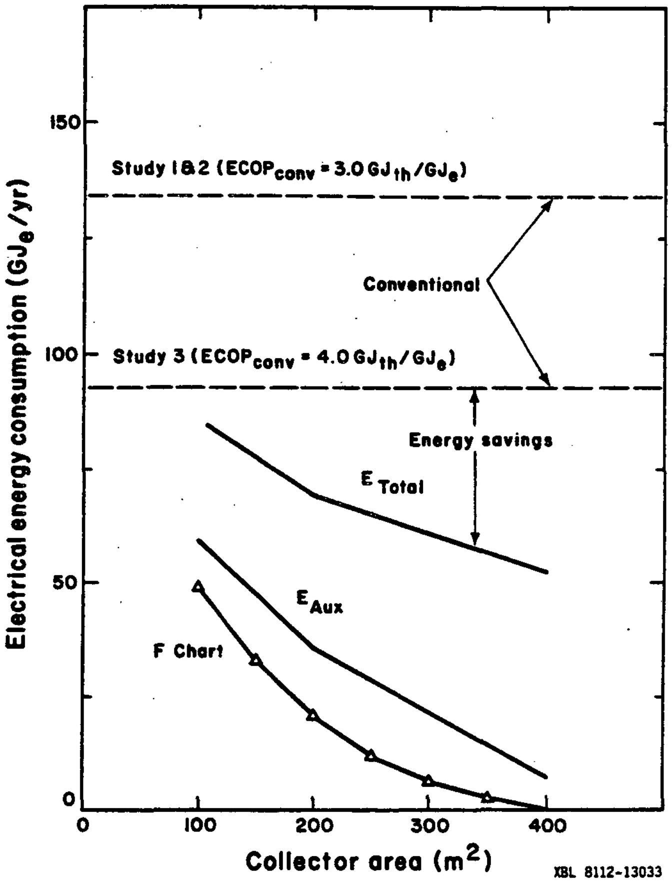

Figure 4. Electrical energy consumption (GJ_e/yr) for a 25 ton solar absorption cooling system with electrical vapor compression backup in Phoenix as a function of collector area.

array is calculated by FCHART 4.0 and the remaining energy is provided by natural gas with a combustion efficiency of 0.8. As shown in Figure 2, the predictions for natural gas consumption using FCHART 4.0 are slightly lower, but in general agreement with the more recent TRNSYS simulations of studies 2 and 3.

The detailed simulations were also performed for the case when the auxiliary cooling was provided by a parallel electrically driven vapor compression chiller, rather than by providing natural gas to the absorption chiller. Figure 4 shows the total electrical energy, E_{TOTAL}, to run the solar system, including the auxiliary energy, E_{AUX}, to run the backup chiller. Also shown in Figure 4 are the results of FCHART 4.0 analysis where the unsatisfied cooling demand is met by a vapor compression chiller with an operating energy efficiency ratio, $ECOP_{conv}$, of 4.0 GJ_{th}/GJ_e (Btu_{th}/Btu_e). The FCHART 4.0 analysis predicts an auxiliary energy consumption that is somewhat lower than that given by the detailed TRNSYS simulation.

Figure 4 illustrates two important facts: 1) Improvement in the performance of conventional chillers reduces the amount of energy that can be saved by an active solar system; and 2) The electrical energy used by the active solar system, as simulated, remains large even for large collector areas where auxiliary cooling energy is minimal.

To analyze the electrical consumption of the active solar cooling system, the different components of the electrical energy consumption are plotted in Figure 5 for a commercial solar absorption cooling system in Phoenix against the fraction of the load met by solar, f_{solar}. Shown on the figure are: 1) The conventional chiller energy, E_{CONV} ($ECOP_{conv}$ 4.0); 2) the auxiliary energy consumption, E_{AUX}, of the parallel backup vapor compression chiller; 3) the parasitic power for the collector loop and the solar absorption chiller, E_{ABS}; 4) the cooling fan power E_{FAN}; and 5) the total electrical energy, E_{TOTAL}, to operate the solar system. The fan and compressor motor energy to run the conventional chiller are also plotted as dashed lines at zero solar fraction.

The solar system takes a penalty of the order of 3 to 10 GJ_e/year on cooling tower fan power, E_{FAN}, because of the larger heat dissipation requirements of the absorption chiller. The auxiliary energy to run the backup chiller, E_{AUX}, is very close to the fractional usage of the conventional chiller, E_{CONV}.

The parasitic power of the collector loop and the solution pumps of the absorption chiller, E_{ABS}, is a critical factor limiting the energy savings capabilities of active solar air conditioning. As shown in

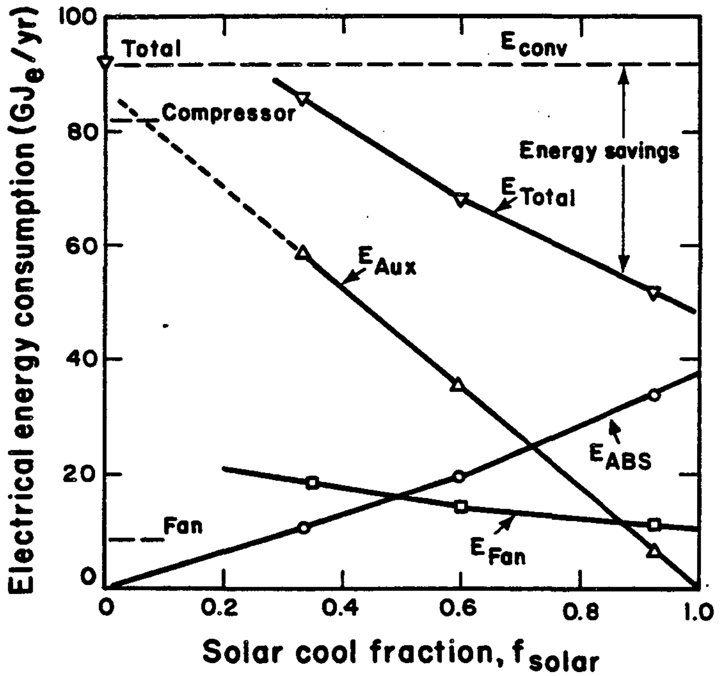

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Figure 5. Electrical energy consumption (GJ$_e$/yr) for a 25 ton solar absorption cooling system with electrical vapor compression backup in Phoenix as a function of solar cooling fraction, f_{solar}.

Figure 5, this energy use is almost linearly proportional to the solar fraction, f_{solar}.

The electrical coefficient of performance of the conventional backup vapor compression chiller, $ECOP_{conv}$, is given by the ratio of the cooling effect produced, Q_{cool}, to the electrical energy supplied to the chiller, E_{conv}.

$$ECOP_{conv} = \frac{Q_{cool}}{E_{conv}} = 4.0\ GJ_{th}/GJ_e$$

The electrical coefficient of performance of the solar fired absorption chiller, $ECOP_{solar}$, is given by the ratio of the cooling effect produced, Q_{cool}, to the electrical energy supplied to the chiller, E_{solar}. Using the thermal performance results for an absorption chiller with 400 m^2 of collectors, $ECOP_{solar}$ is

$$ECOP_{solar} = \frac{Q_{cool}}{E_{solar}} = \frac{338\ GJ_{th}}{33.5\ GJ_e} = 10.0\ GJ_{th}/GJ_e$$

The thermal efficiency of the solar fired absorption chiller, COP_{abs}, is given by the ratio of the cooling effect produced, Q_{cool}, to the energy supplied to the generator of the chiller, Q_{gen}. Using the thermal performance results for an absorption chiller with 400 m^2 of collectors, the solar energy efficiency ratio is given by

$$COP_{abs} = \frac{Q_{cool}}{Q_{gen}} = \frac{338\ GJ_{th}}{486\ GJ_{th}} = 0.70$$

ENERGY EFFECTIVENESS

The energy effectiveness of a solar cooling system depends on the difference between the electrical energy required to deliver solar cooling, and the energy required to deliver the same cooling by conventional means.

$$E_{save} = E_{conv} - E_{solar} = \frac{Q_{cool}}{ECOP_{conv}} - \frac{Q_{cool}}{ECOP_{solar}}$$

To determine the value of solar energy delivered to the generator one can compute the electrical energy that is saved. The cooling delivered, Q_{cool}, is proportional to the energy delivered to the generator, $Q_{cool} = COP_{abs} {*} Q_{gen}$. The electrical energy saved by a solar fired absorption chiller per unit collector area, A, is given by

$$E_{save}/A = \left[\frac{1}{ECOP_{conv}} - \frac{1}{ECOP_{solar}}\right] (COP_{abs} {*} Q_{gen}/A)$$

This analysis can be applied to determine the value of evacuated tube collectors used to drive an absorption chiller at 195 °F. Based on the SAI analysis[6], the energy delivered to the generator for Phoenix with 200 m^2 of collectors, is

$$Q_{gen}/A = 313/200\ GJ_{th}/m^2\text{-}yr$$
$$= 1.57\ GJ_{th}/m^2\text{-}yr\ (138\ kBtu_{th}/ft^2\text{-}yr).$$

The electrical energy saved per unit collector area is then

$$E_{save}/A = 164\ MJ_e/m^2\text{-}yr = 14.5\ kBtu_e/ft^2\text{-}yr.$$

From Table 1, the 20 year present value of saving electricity in the year 2000 with a 11.4 % real return on investment is about \$340./ GJ$_e$/yr (\$360./ MBtu$_e$/yr). The value of energy supplied to the generator by the collector installed in the year 2000 is about \$56./m^2 (\$5.20/ft^2). This is sensitive to the efficiencies of the conventional and solar cooling systems and depends on the thermal efficiency of the absorption chiller. If the $ECOP_{solar}$ is increased to 20, the energy saved increases to 220 MJe/m^2-yr and the value of the energy collected increases to \$75./m^2 (\$7.00/ft^2). The value of the energy collected is directly proportional to both the coefficient of performance of the absorption chiller, COP_{abs}, and on the energy collected per unit collector area, Q_{gen}/A. If COP_{abs} could be increased from 0.7 to 1.6 as the result of improvements in chiller technology [8,9] and if the collector efficiency could be increased by 30% as the result of improved optical and thermal efficiencies of integrated CPC collectors [10], then the value of energy collected would be increased by a factor of 3, going from \$6-7 /ft^2 to \$18-20 /ft^2 .

The value of the energy collected by the active solar cooling system determines the acceptable incremental cost of the installed system over the cost of the conventional system providing the same service. This underscores the importance of increasing the electrical and thermal efficiencies of absorption solar chillers and of reducing the costs and improving the performance of the collector array in improving the economics of active solar cooling systems. As the energy efficiency of conventional air conditioning improves, the value of the thermal energy delivered from the collectors to the generator decreases.

Present costs of solar cooling systems are high, which is characteristic for costs of first generation products of an emerging technology. Today's installed collector costs of \$25 to \$40/ft^2 for evacuated tube or trough collectors must clearly be reduced to make solar cooling cost effective. A key to low cost collectors is the use of lightweight and inexpensive materials. The Low Cost Collector Program has recently projected [11] the manufacturing cost of a trough collector with a lightweight reflector and iron pipe absorber at \$6-8/ft^2. A recent evaluation of the potential for cost reduction indicates that with automation and a production volume of greater than 200,000 panels per year in a single facility, the cost of evacuated tube collectors can be reduced to \$6.50/ft^2 [12]. Work underway at Brookhaven National Laboratory [13] is directed towards developing very low cost (installed cost of \$6/ft^2 or less) collectors which may be suitable for solar cooling applications at 195 °F if their performance is sufficient at these temperatures.

COMPARISON OF DIFFERENT SYSTEMS

Figure 6 shows the electrical energy consumption for three different solar systems that satisfy a 363 GJ$_{th}$/yr cooling load in Phoenix, as taken from the recent SAI study[6]. As expected, the energy required to satisfy the cooling load decreases with increasing collector area. At large collector areas, the Rankine systems can produce surplus electricity and consequently have much lower purchased energy requirements.

With 400 m^2 of collector the 300°F Rankine system saves about twice the energy of the 195 °F Rankine and absorption system. Also plotted on the graph is the results from the commercial Rankine system considered in Study 1, which was used to establish preliminary cost goals. As the result of detailed analysis of parasitic power requirements, the new study thus predicts almost twice the backup energy use compared to the earlier study. Because of these greater solar system electrical energy requirements, coupled with reduced conventional energy requirements (improved conventional ECOP$_{conv}$=4.0), the energy savings predicted are much less than those of the earlier studies.

Figure 7 shows the incremental system cost goals as a function of year of purchase for a 25 ton solar commercial cooling/heating system with 400 m^2 of collector for absorption systems (A) in four cities, and for low temperature Rankine (L) and high temperature Rankine (H) systems in Phoenix. Except for the high temperature Rankine system, the incremental system cost goals for all of these are lower than the preliminary cost goal[2] derived from earlier simulation results. Of the solar absorption systems, the system in Washington, DC performs best because solar is used for both heating and cooling. It should be noted that because of the much higher parasitic power consumption, significant energy savings require 400 m^2 of collector area, rather than the 150 m^2 used for the preliminary cost goals. For an absorption cooling/heating system in Washington, DC this establishes an incremental cost goal of \$65./m^2 of collector or \$1040./ton of cooling (in \$1980).

SUMMARY AND CONCLUSIONS

Recent TRNSYS simulations predict reduced energy savings for active cooling and heating systems primarily because of increased estimates of parasitic power consumption and the use of more efficient conventional air conditioning for comparison. It is important to validate the TRNSYS simulation against real system data to establish that the projected energy savings are correct. In new chiller development critical attention must be paid to reducing parasitic power consumption and improving the coefficient of performance of the absorption chillers if cost competitiveness is to be obtained. For the collection of solar energy to be cost effective as a heat source to drive an absorption chiller at 195 °F, the performance of the collectors must be improved and the costs of collector arrays and other solar system components must be brought down. With current chiller technology the incremental solar system costs, which are dominated by the collector costs, must be reduced to \$5/ft^2 to \$7/ft^2. With advanced chillers and collectors the system costs must be reduced to \$18/ft^2 to \$20/ft^2.

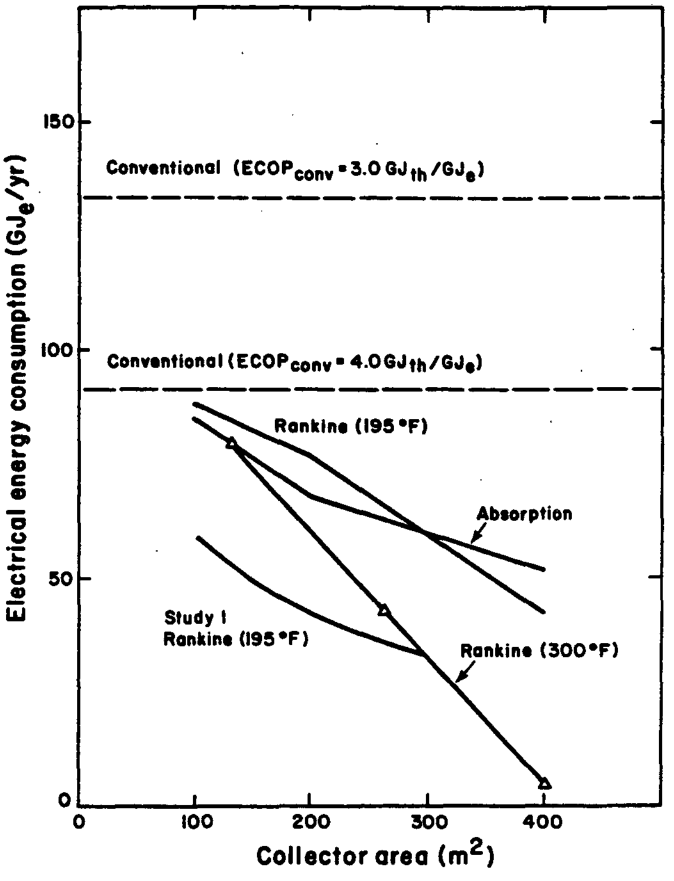

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Figure 6. Comparison of electrical energy consumption (GJ$_e$/yr) of different 25 ton solar commercial systems in Phoenix with electrical vapor compression backup as a function of collector area.

REFERENCES

[1] Warren, M. L., and Wahlig, M., "Methodology to Determine Cost and Performance Goals for Active Solar Cooling Systems." Paper 81-WA/Sol-32 presented at the ASME Winter Annual Meeting, Solar Energy Division, 15-20 November 1981, Washington, DC. LBL-12343. July 1981.

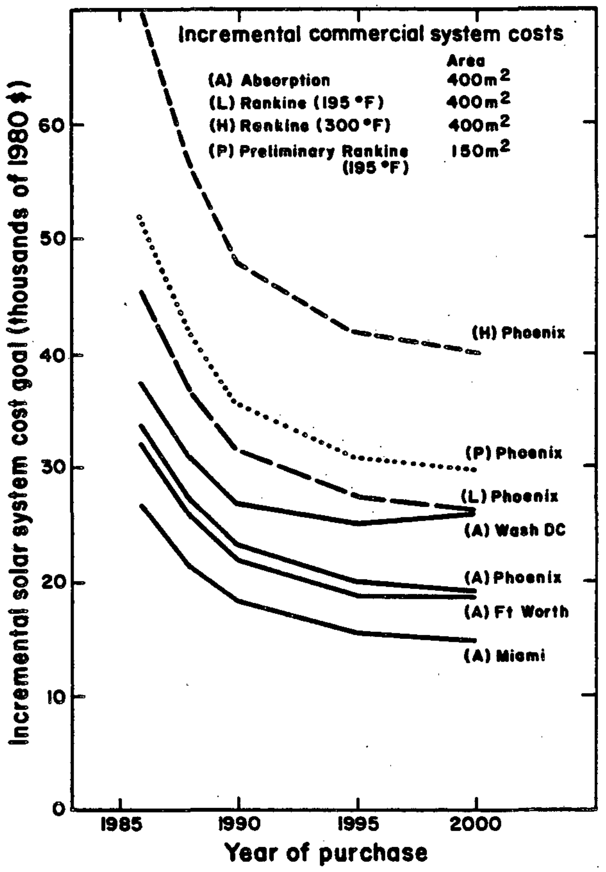

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Figure 7. Incremental solar system cost goals as a function of year of purchase for various systems.

[2] Warren, M. L., and Wahlig, M., "Cost and Performance Goal Methodology for Active Solar Cooling Systems," LBL-12753. December 1981.

[3] Lilian, G. L., and Johnston, P. E., "A Market Assessment for Active Solar Heating and Cooling Products, Category B: A Survey of Decision Makers in the HVAC Market Place," OR/MS Dialogue, Inc., Final Report DOE/CS/30209-T2, September 1980.

[4] Versteegen, P. L., and Morehouse, J. H., "A Thermal And Economic Comparative Analysis of Absorption and Rankine Solar Cooling Systems for Commercial Buildings," Draft Final Report May 1979.

[5] Hughes, P. J., et. al., "Evaluation of Thermal Storage Concepts for Solar Cooling Applications", Science Applications, Inc., Final Report, January 1981.

[6] Morehouse, J. H., and Hughes, P. J., "Status of Several Solar Cooling Systems with Respect to Cost/Performance Goals," Science Applications, Inc., Draft Final Report, August 1981.

[7] LeBoeuf, C., "Standard Assumptions and Methods for Solar Heating and Cooling System Analyses," SERI Report SERI/TR-351-402, January 1980.

[8] Dao, K., "A New Absorption Cycle: The Single-Effect Regenerative Absorption Refrigeration Cycle," Lawrence Berkeley Laboratory Report, LBL-6879, 1978.

[9] Dao, K., "Conceptual Design of an Advanced Absorption Cycle: The Double-Effect Regenerative Absorption Refrigeration Cycle," Lawrence Berkeley Laboratory Report, LBL-8405, 1978.

[10] Winston, R. and O'Gallagher, J., "Engineering Development Studies for Integrated CPC Arrays," Proc. Annual DOE Active Solar Heating and Cooling Contractor's Review Meeting, September 1981, CONF.810912-Prelim, pp.8-8 - 8-10.

[11] Barry Butler, SERI, Private Communication.

[12] Jacobsen, A. S., and Ackerman, P. D., "Cost Reduction Projections for Active Solar Systems," Proc. AS/ISES 1981 Annual Meeting, Philadelphia, PA., pp.1291-1300.

[13] Andrews, J. W., and Wilhelm, W. G. "Thin-Film Flat-Plate solar Collectors for Low-Cost Manufacture and Installation," Brookhaven National Laboratory report BNL 51124, March 1980.

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