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SOLAR ASSISTED HEAT PUMP PROGRAM OVERVIEW AND SUMMARY OF WORK AT BROOKHAVEN NATIONAL LABORATORY

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MASTER

PRESENTED AT THE ANNUAL DOE ACTIVE SOLAR HEATING AND COOLING CONTRACTORS' REVIEW MEETING - INCLINE, NEVADA
March 26-28, 1980

DEPARTMENT OF ENERGY AND ENVIRONMENT

BROOKHAVEN NATIONAL LABORATORY
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SOLAR ASSISTED HEAT PUMP PROGRAM OVERVIEW
AND SUMMARY OF WORK AT BROOKHAVEN NATIONAL LABORATORY*

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PROGRAM OBJECTIVE

The objective of the solar assisted heat pump program is to produce an energy efficient HVAC system utilizing solar energy and electric powered heat pumps which will be optimized according to the following criteria of merit:

1. Cost: When first cost, maintenance cost, and energy cost are considered, the system must be competitive with air-to-air heat pumps.
2. Performance: The system must provide a comfortable living space and adequate hot water.
3. Reliability: The system must have a low failure rate and acceptable system life.
4. Utility impact: Widespread use of the system must not impair, and should improve, the load factor of the electric utility serving the community. This consideration can affect considerably the cost calculations specified in the first criterion.

PROGRAM BACKGROUND

It is possible to view much of the work of the last two years on solar assisted heat pump (SAHP) systems as an attempt to address a single fundamental question: What does one do when the sun isn't shining and storage is depleted? Studies based on the assumption that electric resistance is used as the backup heat source have generally concluded that the SAHP is not a good idea. However, it is now possible to identify four generic paths which have been taken to avoid this difficulty. These are:

1. Bimodal SAHP systems
2. Direct-expansion solar collector/heat pump systems
3. Volume-dominated ground-coupled systems
4. Area-dominated ground-coupled systems

Each type of sysem has its own special characteristics. These are described below.

Bimodal System. I use the term bimodal to describe a system in which the heat pump processes solar-derived heat from storage as long as the storage temperature is above a preset minimum, and some type of backup heat source takes over when the storage temperature falls below this minimum. This is the basic SAHP system, with the proviso that the backup heat source need not be electric resistance, with a coefficient of performance (COP) equal to 1, as has been assumed by most previous studies of SAHP systems.

Recent study[1] has shown that a backup heat source with a COP of 1 (electric resistance) is a poor backup to a SAHP system. It has also been shown that a relationship exists between the COP of the backup and the optimum temperature at which solar energy should be collected and used; this temperature can be controlled by setting the minimum storage temperature below which the system goes to auxiliary. Backup with a COP greater than 1 can be achieved either by using the heat pump to process an alternate source of low-grade heat, or, on a primary energy basis, by using a fossil-fueled burner. The numbers at the left of Fig. 1 show the relationship between optimum storage temperature and backup COP. For this example, which was done for Madison, Wisconsin, an auxiliary COP of 2 results in optimum storage temperatures of from -5 to 11°C in midwinter, the range depending on collector characteristics. If the auxiliary has a COP of 3, the optimum storage temperature is 21 to 39°C. In the first case, a heat pump is needed to process the heat to the load; in the second case the optimums are close enough to what is required for direct heating that is probably pays to go to direct heating. Thus, the optimum system configuration can depend in detail on what is used as backup. A second result seen from Fig. 1 is that as the efficiency of the auxiliary increases, the energy which can be saved by the SAHP system decreases relative to use of the auxiliary only. There are two reasons for this. First, with a more efficient auxiliary there is simply less room for conservation since the auxiliary is now by itself relatively energy efficient. Second, the SAHP, in order to compete with the auxiliary, must operate at higher source temperatures in order to provide COP's that are attractive relative to the auxiliary. Operating at higher source and collection temperatures, the SAHP system will now collect and use less solar energy than before.

Fig. 1 may also be used in a slightly different way. One can compute an economic COP of the auxiliary based on the ratio of the cost of energy provided by the backup to the cost of electricity used to run the SAHP. Then the operating temperatures would be optimized with respect to cost and the vertical axis would represent dollars saved rather than Btu's. In this case off-peak electric resistance supplied at 1/2 the on-peak rate would have a COP of 2. Natural gas costing $4/million Btu (after conversion) would have a COP of 5 relative to electricity costing $20/million Btu. In the first case the SAHP could provide substantial operating cost savings relative to use of the off-peak resistance alone, whereas in the second case the SAHP could not compete.

Bimodel systems can be of interest to electric utilities because they avoid the impact of everyone going to on peak electric resistance at the same time during very cold ambient conditions, as can happen

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with air-to-air heat pumps. Of course, bimodal air-to-air heat pump systems with fossil fueled backup are also possible and the bimodal SAHP must compete with them.

Direct-Expansion Solar Collector/Heat Pump. In this type of system, exemplified by the Sigma Research, Inc. system described elsewhere in these proceedings, the collector itself is used as the heat pump evaporator. Refrigerant in the vapor compression loop is passed through finned tubes exposed to the sunlight; absorbed solar energy evaporates the refrigerant directly, without intermediate storage or heat exchangers. These systems are seen as especially suited for areas such as the Pacific Northwest, with high humidity and rainfall, moderate winter temperatures, and relatively low insolation rates.

Volume-Dominated Ground-Coupled SAHP. In this system concept a large volume of water thermally coupled to the ground is used as the storage element in the SAHP system. Examples of this type of system are the Kaman Sciences systems, using large uninsulated buried tanks, which are described elsewhere in these proceedings, and systems which use a swimming pool as the storage element. Advantages of this type of system are:

1. The cost of storage in dollars per gallon is much less than that of conventional insulated storage. In the case of the swimming pool whose cost is justified by its recreational value, the cost of storage is close to zero.

2. The potential for long term storage (weeks to months) of low grade heat exists. Energy collected at times when the solar collectors are underutilized may be saved for times when they are overworked. The extent of this potential is still under investigation.

3. The system can be designed so that no electric resistance backup is required. This has great advantage to the load factor of the electric utility which is coupled to the system, since heat is always supplied by the heat pump at a high COP, meaning that more customers can be served by the same electric power generating capacity.

Area-Dominated Ground Coupled SAHP. In this system a relatively small amount of heat-transfer fluid is spread out to present a large area, relative to its volume, to the ground. The typical configuration is a serpentine coil of buried plastic pipe, although others are possible. Here the ground is used as a source of heat (or heat sink during the cooling season). Such systems have been installed both in the U.S. and Europe and have performed well. Even without solar input such systems have provided seasonal performance factors in the heating mode in the range 2.5 to 3.0. In colder climates the heat-transfer water which is passed through the pipes must contain antifreeze, and during the depths of winter the ground will be frozen. Minimum source temperatures to the heat pump of $\sim -5°C$ are encountered. If the heat pump and ground coil are sized to meet the design heating load at the minimum ground source temperature, high seasonal performance factors are obtained by avoiding the energy-consuming defrost cycle and the need for supplemental resistance heating, both of which seriously degrade the performance of ait-to-air heat pumps.

If it is desired to add solar energy to such a system to improve performance further, it must be done in such a way that the added cost of the solar components is justified by the additional energy saved. Since the nonsolar ground coupled system is already quite efficient, this is a far more severe test than competing with electric resistance. There are, however, at least three different avenues to coupling solar energy to such a system, and there is hope that one or more will prove competitive. These are:

1. Use of an active solar system to provide space heat and hot water, with the ground coupled heat pump used as backup and for cooling. The solar derived heat could be provided directly to the load; it could be processed through the heat pump at lower source temperatures; or it could be used to preheat the incoming room air, with the ground coupled heat pump boosting the temperature of the air stream to the service value.

2. Use of the most inexpensive passive solar concepts in the building design, with the ground-coupled heat pump providing backup heat, hot water, and cooling.

3. Use of photovoltaics to provide electricity to drive the ground-coupled heat pump.

SUMMARY OF WORK AT BNL

Work at BNL has proceeded in three areas related to SAHP systems - heat pump development, ground coupling, and low-cost collectors for use with such systems - together with necessary analysis work to enable these components to be combined into optimal systems. The heat pump work will be described by E. A. Kush in the following paper. The remaining work is described below.

Study of Ground Energy Coupling Techniques and Their Effect on Solar Assisted Heat Pump Systems. There are presently nine solar ground coupling heat flow experiments in operation at Brookhaven National Laboratory (BNL), including 5 "fields" of serpentine nominal size 1 1/2 in. polyethylene pipe, and 4 buried tanks made from precast concrete rings. The fields, three of which contain an antifreeze solution, are buried at depths of from 2 ft to 12 ft with lengths from 300 ft to 900 ft. The tank volumes are 2200 and 3600 gallons. The experiments are arranged in a circle and connected to a central hub where heat pumps and hot water heaters are used to remove heat from or add heat to the experiments, as dictated by computer simulations of ground coupled solar heat pump systems. Thus the value of various control strategies including summer storage of solar heat for winter use, space cooling heat rejection to the ground, and summer daytime storage of heat for nocturnal rejection, are experimentally tested.

Heat flow rates, water flow rates, experiment temperatures and ground temperatures are all measured. Soil property experiments have been conducted to determine soil heat capacity, density, moisture content, thermal diffusivity, and (indirectly) thermal conductivity. Additional advanced heat flow and soil property experiments are planned.

One important research effort at BNL has been the development of a validated model of ground coupling. A flexible, 3-dimensional finite element computer program called GROCS has been written to model ground coupling devices. GROCS was subsequently integrated[2] with the solar system simulation program

TRNSYS so that complete ground coupled solar heat pump systems can now be simulated. The GROCS-TRNSYS program with documentation is publicly available. Papers which describe the design, construction and operation of these experiments,[3] computer simulation results,[4] experimental results,[5] and experimental versus computer model comparisons are available.[6]

Heat Pump Impact Upon Solar Collector Design and Cost. This project has involved a program of analysis to determine appropriate cost and performance goals for collectors used in the systems under study at BNL. A companion effort to develop low-cost collectors which, if successful, will meet these cost and performance goals was also initiated.

The flat-plate solar collectors under development depart radically from conventional designs.[7] High-performance thin-film plastics (0.001 to 0.010 in.) are used in the glazing and absorber portions of these collectors in order to reduce cost. These plastic films are attached to a light rigid frame by means of a pressure-sensitive adhesive or other sealer which functions as both fastener and weather seal. The attached films form a set of stressed membranes that contribute to the overall strength of the panel. this monocoque construction provides a complement of physical properties which reduces material requirements and lowers fabrication costs.

In this solar collector design water is used as the liquid heat-exchange medium. It enters the absorber through manifolding integrated into the frame. The water enters the collector from the top manifold and flows between the two absorber films. A layer of aluminum foil laminated to the upper plastic layer in the absorber provides good lateral heat transfer from unwetted to wetted areas. Solar-heated water flows to the bottom of the collector and then out through manifolding similar to that at the top, but with larger porting to ensure adequate drainage.

The solar collectors made with thin plastic films have several advantages over conventional flat-plate collectors:

1. A reduction in material costs;
2. A large reduction in collector weight and bulk, which make installation easier and less expensive;
3. Potentially enhanced performance because of good-to-excellent physical properties such as high glazing transmissivity (to 96%) and good thermal heat transfer;
4. Potentially high reliability and good production yield because the absorber requires essentially no internal pressurization and the construction is uncomplicated;
5. Tolerance of the absorber to freezing temperatures without the addition of antifreeze agents.

The major factor limiting the use of thin plastic films in a solar flat-plate collector is their environmental tolerance. The glazing films must be able to withstand high temperatures, weather, corrosive agents, and ultraviolet light for an extended period. The absorber, which is somewhat protected from weather and ultraviolet, must be resistant to the effects of fluid flow and of long-term exposure to high temperatures under conditions of thermal stagnation.

TECHNICAL ACCOMPLISHMENTS

The following major technical accomplishments can be listed:

1. The ability of the vapor compression cycle to provide the high predicted COP's at high source temperatures has been confirmed. See the following paper by E. A. Kush for details.
2. The ability of a ground-coupled pipe coil to provide acceptable rates of heat transfer has been demonstrated. Rates of $\sim$ 2 Btu/°F-hr-ft pipe are consistent with results elsewhere; the temperature difference is taken between the ground coupling device and the temperature of undisturbed ground at the same depth and time of year (far-field temperature).
3. A low-cost collector using thin-film plastics in both the absorber and glazings has been constructed and tested. Fig. 2 shows predicted performance curves for single and double glazed collectors, together with test data for a double glazed model.
4. A computer model of ground coupled systems (both area-dominated and volume-dominated) has been developed and integrated into TRNSYS.
5. A simplified analysis method for optimizing SAHP systems has been developed. Fig. 1 was one of the results of this analysis.

FUTURE ACTIVITIES

Activities in the following major categories will be pursued:

1. Upgrading of the solar heat pump simulator, continued evaluation of vapor compression cycle performance, and testing of the Northrup prototype heat pump (see dollowing paper for details).
2. Continued collection and analysis of ground coupling data and use of these results to validate and improve ground heat flow models. In conjunction with other projects monitored by BNL, a first generation of design guidelines will be developed.
3. Further development of the low-cost collector and investigation of suitable polymeric materials.
4. Simplified analyses as required to integrate system components and to make possible proper program direction.

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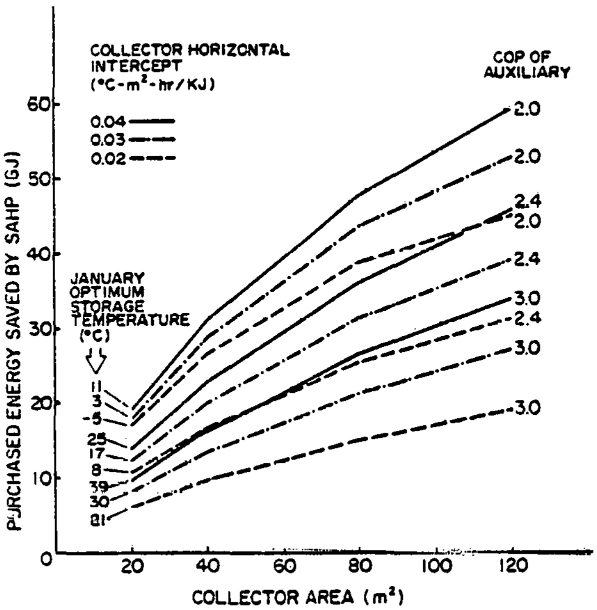

Figure 1. Purchased Energy Saved by SAHP Relative to Use of Auxiliary Only, Without SAHP

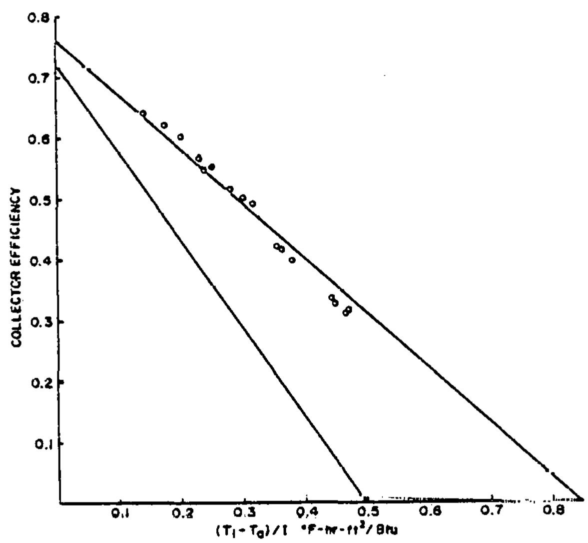

Figure 2. Calculated Efficiency Curves for BNL Low-Cost Collector, Single and Double Glazed, with Test Data Points for Double Glazed Collector