

DOE/NASA CONTRACTOR REPORT

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APPLICATION OF SOLAR ENERGY TO AIR CONDITIONING SYSTEMS

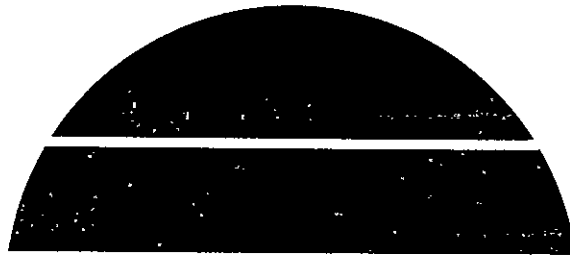
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Solar Energy

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| 16. ABSTRACT The results of a survey of solar energy system applications of air conditioning are summarized. Techniques discussed are both solar powered (absorption cycle and the heat engine/Rankine cycle) and solar related (heat pump). Brief descriptions of the physical implications of various air conditioning techniques, discussions of status, proposed technological improvements, methods of utilization and simulation models are presented, along with an extensive bibliography of related literature. | | |
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INTRODUCTION AND SUMMARY

This report summarizes the results of a survey of solar energy system applications of air conditioning. This effort was conducted in support of IBM's system analysis activities which are a part of the Systems Integration of Marketable Subsystems program at Marshall Space Flight Center in Huntsville, AL. This review has been primarily directed toward those air conditioning techniques deemed most likely to find residential application in the near (5-year) term and which are compatible with the solar energy systems expected to result from this program.

The air conditioning techniques discussed are both solar powered (absorption cycle and the heat engine/Rankine cycle) and solar related (heat pump). However, it should be recognized that other methods exist and their omission is not intended to indicate other than the selection criteria described above. Among those omitted are such techniques as: absorptive humidification/dehumidification cycles, rock bed regeneration and nocturnal radiation.

The basic phenomena utilized in absorption air conditioning is similar to that of the heat engine/Rankine cycle and the heat pump in that they each derive their refrigeration effect from the condensation and evaporation of a refrigerant liquid. The essential difference is that the necessary pressure differential within the absorption cycle is provided by a physico-chemical process where the others depend on mechanically operated compressors. This is an advantage as pumping the refrigerant in the form of a refrigerant-absorbent solution requires far less mechanical energy than compressing it as a vapor. Each of these cycles depends on an energy source. The absorption cycle and heat engine/Rankine cycle use heat as their energy source; the heat pump uses electricity.

Subsequent sections present brief descriptions of the physical implications of various air conditioning techniques. Also presented are discussions of status, proposed technology improvements, methods of utilization, and simulation models.

The general conclusion of the studies reviewed is that the application of solar energy to air conditioning systems is an interesting and potentially economically viable concept. However, both the solar powered and the solar related techniques are inherently more complex than standard solar heating systems. Resulting advantages and disadvantages are summarized in Tables I and II. Trends in system technological improvements are summarized in Table III.

TABLE I
POTENTIAL ADVANTAGES OF SOLAR AIR CONDITIONING APPLICATIONS

- Year-round utilization improves "heating only" load factor
- Less severe storage requirements than heating due to load more nearly in phase with available energy
- Consumer usage/demand amount and percentage of energy consumption is growing rapidly
- Reduction of seasonal summer utility peaking
- Low cost increases over conventional heat powered systems
- Generally favorable cost/performance ratio for commercial applications
- Existing detailed simulation capabilities

TABLE II
POTENTIAL DISADVANTAGES OF SOLAR AIR CONDITIONING APPLICATIONS

- "In building" heat losses are detrimental both to system performance and amount of load.
- High performance collectors, high temperature storage, and specialized high technology equipment are all high cost items
- Further extension of technology is hampered by thermodynamic limitations
- Operation of collectors at elevated temperature levels reduces efficiency
- Absorption auxiliary energy mode is less efficient and more costly than competitive systems
- Solar air conditioning is new, different and generally unavailable
- Support services are more technical and more frequent
- Outdoor cooling tower is generally required
- Unfavorable cost/performance ratio for residential solar powered applications
- Rankine cycle and heat pump use flurocarbons for operation
- Load management is critical for efficient operation
- Detailed simulation cost

TABLE III
TECHNOLOGICAL IMPROVEMENTS TREND

- Increase performance by elevating solar heat supply temperature
- Development of techniques with auxiliary energy mode economically comparable with competitive systems
- Cold storage with excessive capacity and/or off peak operation
- Development of higher efficiency heat pumps by using variable speed and compression ratio, larger heat exchangers, and more efficient motors and compressors
- Near term improvements expected in reliability first, then efficiency
- Identification of dual source heat pumps as technically viable

2.0 ABSORPTION COOLING

The most common approach to air-conditioning applications of solar energy uses the absorption air conditioner in conjunction with solar collection and storage subsystems. This would be expected, as the best developed conventional heat-actuated cooling technique today is the absorption cycle.

The absorption cycle (simplified by omission of various heat exchangers) is schematically represented in Figure 2.1 as a series of pressure and heat exchange processes. Heat energy is input to the cycle at the generator. This heating separates the high-pressure, dilute refrigerant-absorbent solution into refrigerant vapor and concentrated (i.e., refrigerant free) solution. The hot, high pressure concentrated solution is used to pre-heat the entering dilute solution and then returned to the absorber through a pressure reduction valve. The hot, high pressure refrigerant vapor enters the condenser where it is condensed to a liquid by rejection of heat to cooling water. The cooled liquid then enters the evaporator at low pressure by passing through an expansion valve. The absorption cycle cooling effect is achieved by the endothermic evaporation process which returns the refrigerant liquid to a vapor. The low pressure refrigerant vapor leaves the evaporator and enters the absorber where it is reabsorbed into the concentrated solution returning from the generator. The heat of absorption is rejected to cooling water and the now dilute refrigerant-absorbent solution is pumped back to the generator. Variation of this procedure include: (1) using ambient air rather than water for cooling, (2) adding a liquid refrigerant recirculation pump to the evaporator, and (3) using low pressure levels in the cycle and eliminating the solution pump by substitution of a heat-actuated vapor lift procedure.

Design constraints of practical solar energy applications of absorption cycles are primarily caused by thermal limitations. These are the thermodynamic properties of the refrigerant-absorbent solution and the effectiveness of heat transfer equipment in the absorption air conditioner. The upper thermal limits of non-pressurized liquid storage and reduced efficiency with elevated temperature of solar collectors serve to compound these limitations. The result of these factors is the trend toward use of improved heat exchangers and a requirement for recirculation of the cooling water through an outdoor cooling tower for heat rejection.

Economic application of absorption cycle cooling is limited by cost of equipment and cost of operation in the auxiliary (non-solar powered) mode. Manufacturers in both the United States and Japan are actively striving to reduce equipment cost. The auxiliary mode operation however, is expected to be the long term limitation to use of the absorption cycle in residential cooling applications.

Simulation of performance of an absorption cycle cooler can be achieved by empirical representation of the unit's operating characteristics based on manufacturer test data. Such a representation is compatible with the modular format required for subsystem simulation by TRNSYS. TRNSYS, the industry standard computer simulation program for solar energy systems, is written to accept user developed modules of this nature. The required data for an absorption machine is a performance map of delivered capacity as a function of (1) hot water, condensing water and chilled water flow and temperature conditions and (2) the rejected heat rate. As both the $\text{LiBr-H}_2\text{O}$ and the $\text{NH}_3\text{-H}_2\text{O}$ cycles are functionally as shown by Figure 2.1, they each meet these modeling requirements.

Absorption air conditioners and associated cooling towers are more expensive to purchase than vapor compression air conditioners of the same capacity. In residential applications this first cost differential has proven to be detrimental to consumer acceptance. Exceptions to this lack of acceptance exist only where low-cost natural gas was available as an alternative to high-cost electricity. For these conditions, or where low-cost waste heat can be used, operating costs of the absorption unit is lower cost than for vapor compression. Where electricity is relatively inexpensive and fuel is reasonably expensive, the electric vapor compression machine is superior.

This section presents a brief discussion of two closed-loop, cooling cycles which are heat-actuated and based on absorption of refrigerant in liquid absorbent solutions. The first is lithium bromide-water ($\text{LiBr-H}_2\text{O}$) where water is the refrigerant and the other is ammonia-water ($\text{NH}_3\text{-H}_2\text{O}$) where ammonia is the refrigerant. In both cases solar energy is used to supply the heat energy to the generator of the absorption unit.

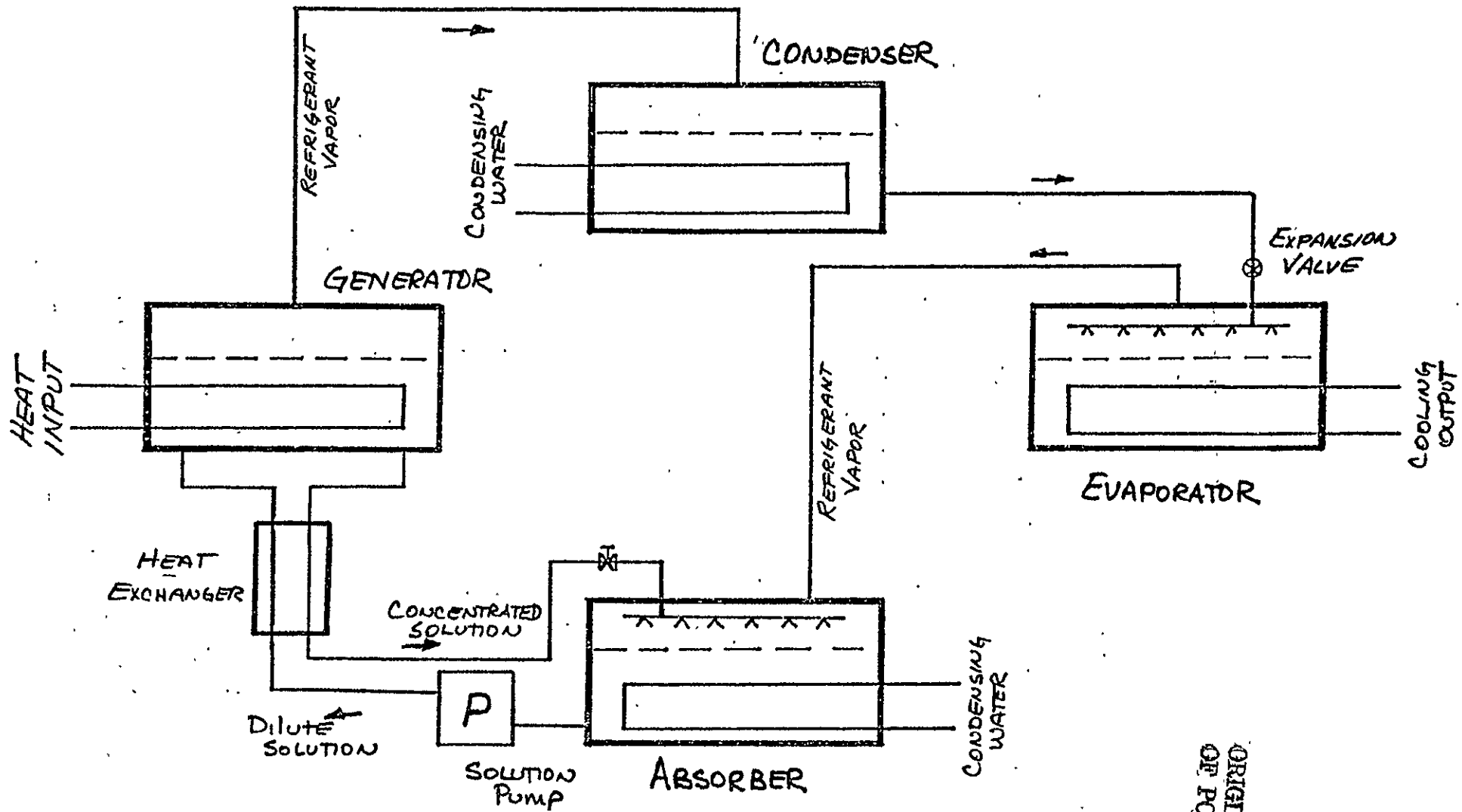


Figure 2.1. Absorption Cooling Cycle

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2.1 LITHIUM BROMIDE - WATER CYCLE

Most solar energy cooling applications to date have used the LiBr-H₂O absorption cycle with water cooled absorber and condenser. This cycle is also the most common conventional cooling application of an absorption cycle technique. This popularity is primarily due to two thermodynamic characteristics of the LiBr-H₂O cycle compared with the NH₃-H₂O cycle. These are: (1) lower generator temperature and (2) lower cycle working-fluid pressure levels. The first characteristic allows operation with generator temperatures of 170 - 210°F versus 205 - 250°F for water cooled and 260 - 340°F for air cooled NH₃-H₂O cycles. The second characteristic allows operation with reduced pumping power.

Arkla Industries has selected this cycle to market for solar energy applications of their absorption machines. They presently have two water fired absorption air conditioning units for use in solar energy installations. These units are the 3-ton 501-WF and the 25-ton WF-400.

Residential application of the 3-ton unit has been limited mainly to research and demonstration projects. A new model 3-ton unit WF-36 is scheduled for volume production and general availability in early 1977. A comparison of the operating characteristics of the two 3-ton models is shown in Table IV and Figure 2.2. The data required for simulation of the WF-36 unit is given in Table V. A Model of the earlier 3-ton unit is contained in the standard TRNSYS library.

TABLE IV

COMPARISON OF SOLAIRE (ARKLA INDUSTRIES)
THREE TON AIR CONDITIONING UNITS

NOTE: 501-WF is Liq/Air and WF-36 is Liq/Liq

| CRITERIA/MODEL | 36 (WF-36) | 501-WF |
|---|------------|-----------|
| DESIGN DELIVERIED CAPACITY, BTUH | 36,000 | 36,000 |
| <u>ENERGY REQUIREMENTS</u> | | |
| DESIGN HOT WATER INPUT, BTUH | 50,000 | 55,000 |
| DESIGN HOT WATER INLET, °F | 195 | 210 |
| PERMISSIBLE RANGE OF INLET, °F | 170-205 | 180-210 |
| DESIGN HOT WATER FLOW, GPM | 11.0 | 11.0 |
| PRESSURE DROP @ 11 GPM, FT H ₂ O | 9.8 | 4.6 |
| MAX. PERMISSIBLE FLOW, GPM | 22 | 22 |
| STD ELECTRICAL VOLTAGE, 60 Hz, 1-Ø | 115 | 115 |
| WATTAGE DRAW | 250 (MAX) | 450 (TYP) |
| <u>CONDENSING WATER DATA</u> | | |
| DESIGN HEAT REJECTION, BTUH | 86,000 | 91,000 |
| DESIGN INLET TEMP., °F | 85 | 85 |
| PERMISSIBLE RANGE OF INLET, °F | 75-90 | 70-85 |
| DESIGN FLOW, GPM | 12.0 | 10.0 |
| PRESSURE DROP @ DESIGN, FT H ₂ O | 9.6 | 4.0 |
| MAX. PERMISSIBLE FLOW, GPM | 25 | 17.5 |

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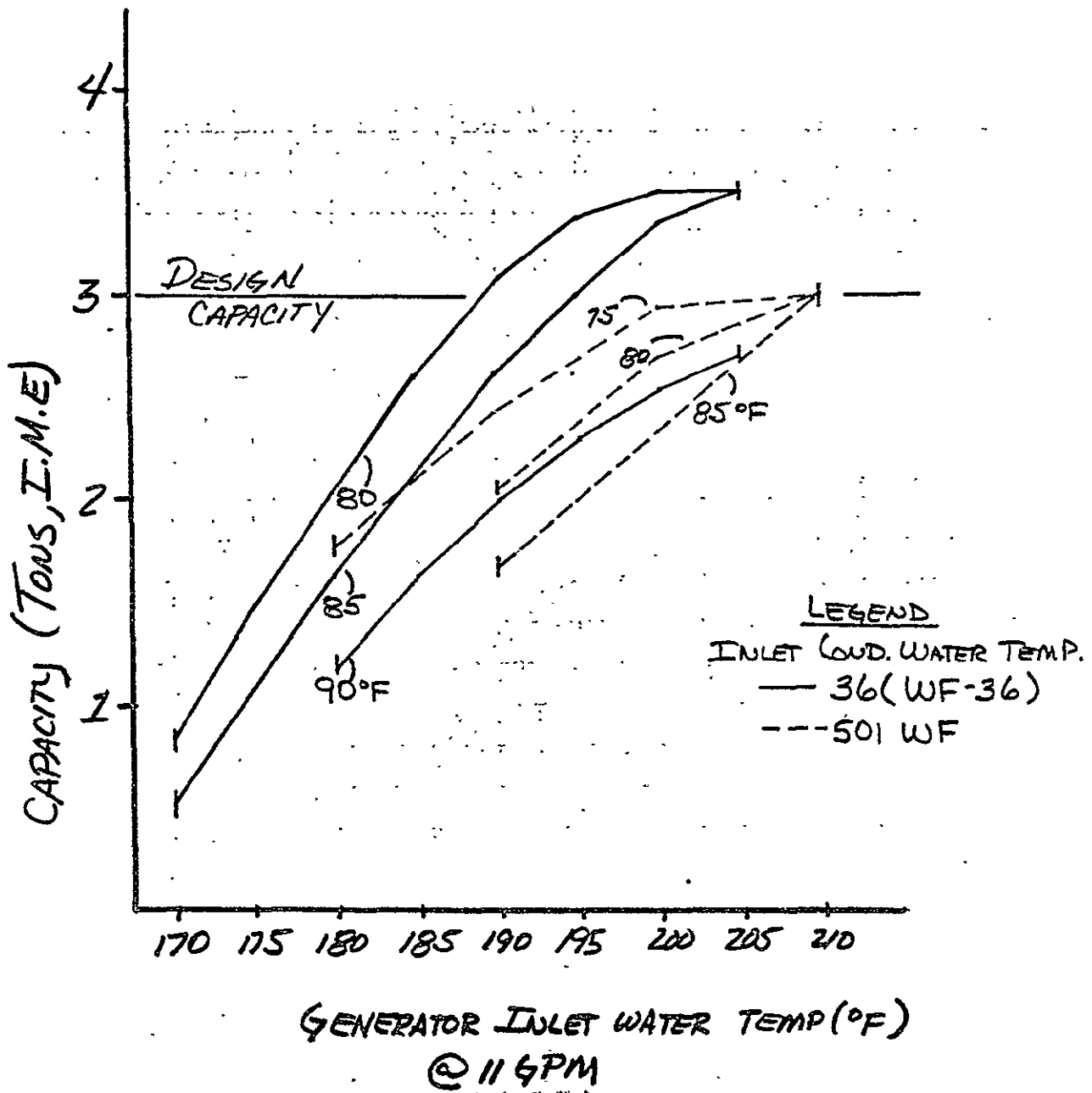


Figure 2.2. Performance Map of Solair (ARKLA Industries) Three Ton Air Conditioning Units

2.2 AMMONIA - WATER CYCLE

The ammonia-water cycle is essentially identical of the LiBr-H₂O cycle. The principal exception is the addition of a rectifier between the generator and the condenser. This rectifier prevents water vapor from entering the condenser since, unlike the LiBr-H₂O cycle, water is not the refrigerant. Because of the high working pressures, mechanical pumps are always required to return the dilute solution from the absorber to the generator.

Only limited solar energy system applications of NH₃-H₂O cycle cooling have been made. The general opinion is that high (over 200°F) generator temperature requirements ammonia-water cycle coolers exclude operation with flat plate collectors. Contrasting with this almost universal conclusion, researchers at the University of Florida report operation with hot water supplies in the 135° to 180°F range. The reason for this disagreement has not been fully determined by this review. However, indications are that higher concentrations of ammonia in the refrigerant-absorbent solution may be the answer.

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3.0 HEAT ENGINE/RANKINE CYCLE COOLING

The most promising solar powered air conditioning alternative to the absorption cycle is the heat engine/Rankine cycle combined with the conventional vapor compression cooling cycle. The Rankine cycle is used to convert solar energy into mechanical energy and thus provide the compressive force needed in the system. Problems associated with this technique are primarily those of the heat engine. Cooling by vapor compression is well established.

The Rankine cycle and vapor compression cycle are schematically represented in Figure 3.1 as a coupled series of pressure and heat exchange processes. Heat energy is input to the Rankine cycle at the boiler. This function is similar to that of the absorption cycle generator except that instead of separating a refrigerant-absorbent solution into a vapor and a solution it converts a pure refrigerant solution entirely into a refrigerant vapor. The refrigerant commonly used is Freon. The hot refrigerant vapor enters the high-pressure inlet of the heat engine's turbine where it expands and produces rotary motion. Still warm, the low-pressure vapor then enters the condenser where it is condensed to a liquid by rejection of heat to cooling water. The liquid refrigerant is then pumped back to the boiler. This portion of Figure 3.1 represents the Rankine cycle used to provide rotary motion from solar energy and thus function as a heat engine.

The rotary output of the heat engine is used to provide mechanical input to the compressor. The compressor is used to raise the very-low pressure of the vapor refrigerant from its evaporator outlet condition to the same pressure level as the turbine expander outlet. The combined vapor flows into the condenser as described above. The vapor compression cycle shown is at a lower pressure than the Rankine cycle. After being condensed to a liquid, that portion of the refrigerant used for cooling is then further expanded through an expansion valve and then enters the evaporator at still a lower pressure. The vapor compression cycle cooling effect is achieved by the endothermic evaporation process which returns the refrigerant liquid

to a vapor. This very low pressure refrigerant vapor leaves the evaporator and enters the low-pressure inlet of the compressor where it is compressed to a pressure compatible to the turbine expander outlet. This portion of Figure 3.1 represents the vapor compression cycle used to convert rotary motion into a cooling effect and thus provide air conditioning. Conventional application of this cycle uses an electric motor to provide the rotary motion.

Many attempts are currently being made to improve the performance of the basic heat engine/Rankine cycle. The most common is using the warm outlet refrigerant vapor from the turbine expander to preheat the liquid refrigerant between the pump and the boiler inlet.

Simulation of performance of heat engine/Rankine cycle cooler can be achieved by empirical representation of the unit's operating characteristics by the method described in Section 2.0. The performance data required is of the same form as that described for the absorption cycle.

Although not presently available in the HVAC market, heat engine/Rankine cycle coolers are expected to become commercially available within the next five years. Their purchase price is expected to be comparable with today's absorption coolers. As such, they would have a higher purchase price than conventional equipment. However, unlike the absorption units, they are adaptable to auxiliary energy input in the form of rotary motion instead of heat. This allows use of an electric motor which reduces the auxiliary mode operating conditions to the same as conventional. The greatest appeal of this concept is not having the auxiliary mode economic penalty of the absorption cycle and thus being a potential candidate for residential application.

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HEAT INPUT

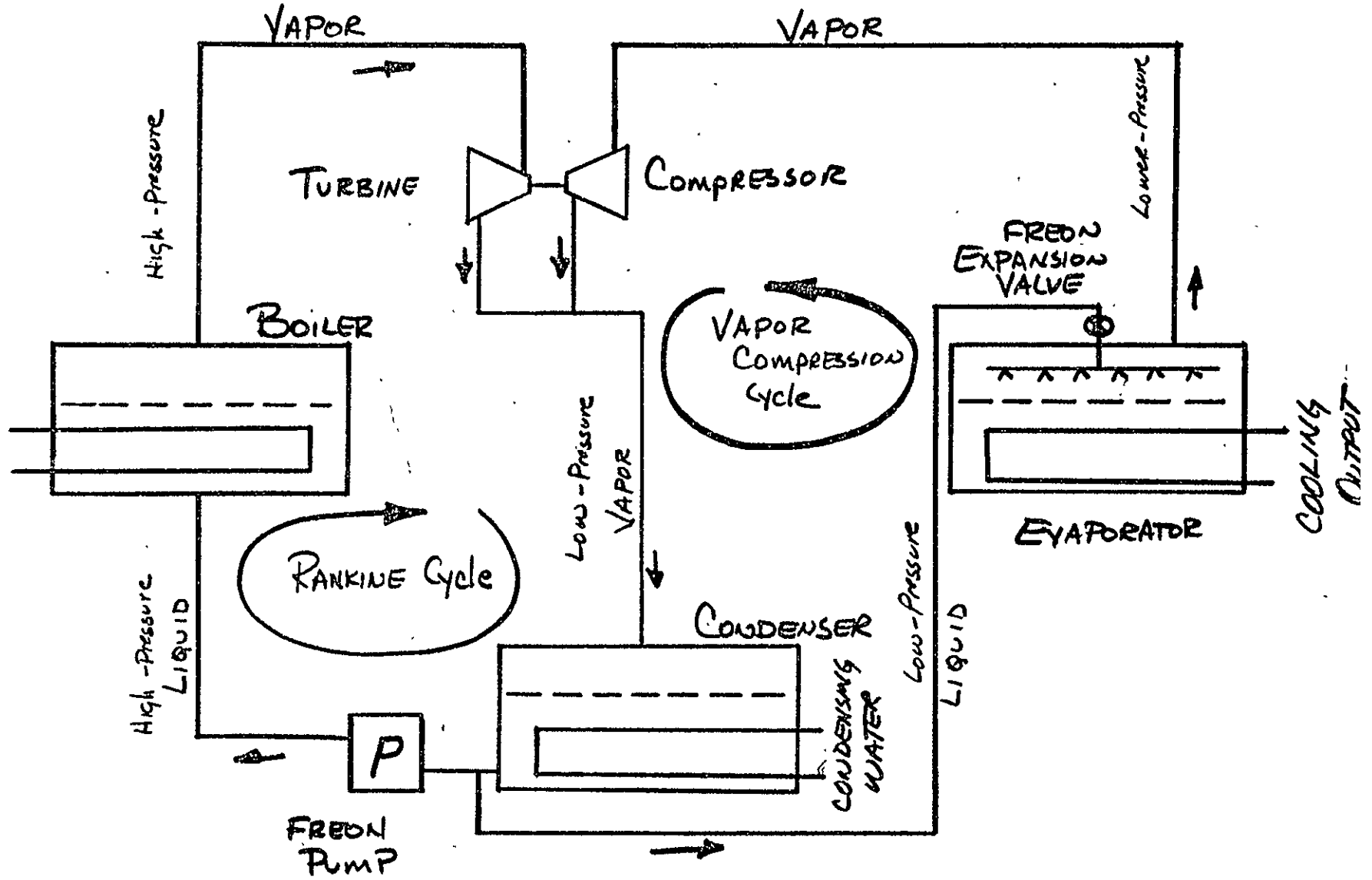


Figure 3.1. Heat Engine/Rankine Cycle Cooling

4.0 HEAT PUMP SYSTEMS

Heat pumps are considered in this solar air conditioning review although they neither derive their operating energy from solar provided heat nor actively interface with the solar energy system while providing cooling. However, they are related since heat pumps have been used as an auxiliary heat source for solar heating systems which can also provide the entire cooling requirement. The cooling method is the conventional vapor compression cycle described in the last section.

Heating with a conventional heat pump is accomplished by reversing the roles of the condenser and evaporator. This rejects the heat of condensation into the area being heated and takes in ambient heat by the endothermic evaporation process. The compressor serves to raise the refrigerant temperature level between ambient and the desired heating temperature.

Heating with a solar-heat pump has been considered in three configurations. These are: (1) in parallel with the solar heating system which uses an ambient temperature heat sink as described above for the conventional case, (2) in series with solar storage tank heat source, and (3) with capability of dual source where the choice of heat sink can be made by comparison of temperature level and the highest is chosen. As with conventional applications of heat pumps, each of these solar configurations require an auxiliary (usually electric resistance heaters) heat source.

For the cases described various ambient media are used for the heat source. The selection for a particular application is determined from considerations of geographic location, climate, cost availability, and type of structure. A comparison of these sources as summarized by ASHRAE is shown in Table V. As indicated, solar heat provides an excellent source when it is available. This is because it is at a relatively high temperature which increases the performance capability of the heat pump. A further benefit of the solar-heat pump system versus a solar heating system without a heat pump is reduction of the required collector temperature. This can provide an increase of collector efficiency and capacity.

Types of solar heat pump systems are classified as direct and indirect. Direct systems use a solar collector/evaporator combination. This is usually designed with no cover plates so it can also be used as a condenser by rejecting heat when in the cooling cycle. Table VI shows various common heat pump types. The circuit used in the direct solar heat pump system may resemble that shown for the earth-to-air heat pump.

Indirect systems employ another fluid to collect heat by circulation through the solar collector. This heated fluid is then used to heat the refrigerant by passage through a heat exchanger. When air is the heated working fluid the first system shown in Table 4.2 for air-to-air may be used. When water is used, either the water-to-air or water-to-water type may be employed. A dual source indirect solar assisted heat pump system is shown schematically in Figure 4.1.

Simulation of performance of solar heat pump systems can be achieved by utilization of the standard TRNSYS library heat pump model. This model can be used for any of the three characteristic types and is devised to accept user-specified performance data from which it derives off-design operational characteristics. The data required are heat added, heat rejected, and total work input over a specified range of source or sink temperatures. Such data are available from the manufacturers of heat pumps which might be selected.

Studies of these configurations have shown solar heat pump systems to be economically feasible throughout much of the United States. The dual source evaporator configuration has been shown superior to either the series or parallel system. Unfortunately, although recognized as analytically desirable, there has not been, as far as can be determined, any residential dual source heat pumps manufactured to date.

Table V. Heat Pump Heat Sources and Sinks

| Heat Source | Air | City Water | Well Water | Surface Water | Waste Water | Earth | Solar |
|----------------------------------|--|---|--|--|---|--|--|
| Source classification | Primary | Primary or auxiliary | Primary | Primary | Primary or auxiliary | Primary or auxiliary | Auxiliary |
| Suitability as heat sink | Good | Good | Good | Good | Variable with source | Usually poor | May be used to dissipate heat to air |
| Availability (location) | Universal | Cities | Uncertain | Rare | Limited | Extensive | Universal |
| Availability (time) | Continuous | Continuous—except local shortages | Continuous—check water table | Continuous | Variable | Continuous, temperature drops as heat is removed, slowly rises when pump stops | Intermittent, unpredictable, except over extended time |
| Expense (original) | Low, less than earth and water sources except city | Usually lowest | Variable, depending on cost of drilling well | Low | Variable | High | High |
| Expense (operating) | Relatively low | High, usually prohibitive | Low to moderate | Relatively low | Low | Relatively moderate | Unexplored. Promising as auxiliary for reducing operating cost |
| Temperature (level) | Favorable 75-95% of time in most of United States | Usually satisfactory | Satisfactory | Satisfactory | Usually good | Initially good—drops with time and rate of heat withdrawal | Excellent |
| Temperature (variation) | Extreme | Variable with location (10 to 25 F deg) | Small | Moderate | Usually moderate | Large—less than for air, however | Extreme |
| Design information | Usually adequate | Usually adequate | Usually adequate | Usually adequate | Adequate if source is constant in supply and temperature | Inadequate | Practically available |
| Size of equipment | Moderate | Small | Small (except for well) | Small | Variable (usually moderate) | Small (except ground coils) | Available in some areas |
| Adaptability to standard product | Excellent, can be factory assembled and tested | Excellent | Excellent (except for well) | Excellent | Poor | Poor | Poor |
| Sources it may augment. | | Air, earth | | | | | |
| Special problems | Least heat available when demand greatest. Coil frosting requires extra capacity, alternate source, or standby heat. May require ductwork. | Scale on coils. Local use restrictions during shortages. Disposal. Water temperature may become too low to permit further heat removal. | Corrosion, scale may form on heat transfer surface. Disposal may require second well. Water location, temperature, composition usually unknown until well drilled. Well may run dry. | Water may cause scale, corrosion, and algae fouling. | Usually scale forming or corrosive. Often insufficient supply. Very limited application, hence required individual design. Freeze-up hazards. | Limited by local geology and climate. Installation costs difficult to estimate. Requires considerable ground area, may damage lawns, gardens. Leaks difficult to repair. | Probably will require heat storage equipment at either evaporator or condenser side. |

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Table VI. Common Heat Pump Types

| HEAT SOURCE AND SINK | DISTR FLUID | THERMAL CYCLE | DIAGRAM | | |
|----------------------|-------------|------------------------|-----------|-----------|-----------------------|
| | | | ⇨ HEATING | ⇨ COOLING | ⇨ HEATING AND COOLING |
| AIR | AIR | REFRIGERANT CHANGEOVER | | | |
| AIR | AIR | AIR CHANGEOVER | | | |
| WATER | AIR | REFRIGERANT CHANGEOVER | | | |
| AIR | WATER | | | | |
| EARTH | AIR | REFRIGERANT CHANGEOVER | | | |
| WATER | WATER | WATER CHANGEOVER | | | |

* ALL SINGLE STAGE COMPRESSION

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(From ASHRAE Systems Handbook, 1976)

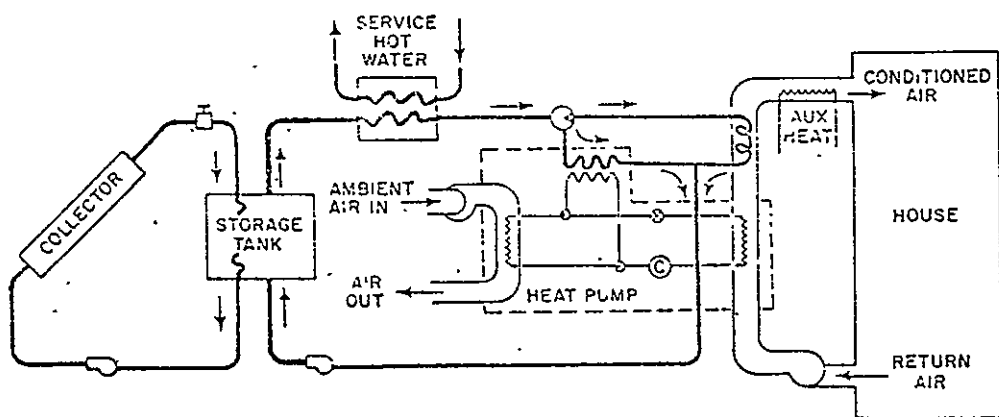


Figure 4.1. Dual Source Solar Assisted Heat Pump
 (From Duffie and Beckman, 1976a)

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5. DISCUSSION AND CONCLUSIONS

Application of solar energy to air conditioning systems is an interesting and potentially economically viable concept. The techniques which have emerged from this survey have demonstrated many conditions for which air conditioning requirements and solar energy system capabilities are closely matched. However, both the solar powered and solar related cooling techniques presented are inherently more complex than standard solar heating systems. This complexity places even more emphasis on both performance and economic considerations for proper evaluation. This section presents some of these considerations and their impact on successful application.

5.1 POTENTIAL ADVANTAGES

Systems which address both heating and cooling requirements generally have year-round utilization. This improves the load factor experienced by the heating only system as the solar equipment is used in the summer cooling season as well as the winter heating season. The exact degree to which the combined heating and cooling system is utilized depends on the specific location and requirements.

Heating systems using solar energy find their greatest loads occurs during the night. This puts constraint on storage subsystem capability. Cooling load normally is greatest in the day. This presents less severe storage requirements since it is more in phase with the availability of solar energy source.

Both the amount of energy required to provide residential air conditioning and the percentage of energy consumed nationally that it represents are growing rapidly. This condition serves to place additional emphasis on all renewable energy source techniques which can provide air conditioning and thus emphasis on solar applications.

In some regions of the country, utilities experience higher demands for energy on a seasonal basis. To the extent that this peaking is attributed to air conditioning and the cooling can be provided by solar energy, the utility load can be leveled. This benefit is viable only when the impact of auxiliary energy requirements are properly considered.

In some applications, normally commercial, the conventional method of air conditioning uses heat powered cooling equipment. In these cases, the increased system cost of adding solar energy as an additional heat source is usually very competitive.

In general, commercial applications offer alternatives for air conditioning system design which make solar energy attractive. Examples of these can be: cooling loads for longer during the year, availability of waste heat, load size that justify larger expenditure for slightly more efficient equipment and the many other reasons that absorption cycle air conditioning is widely used in many many conventional commercial applications today.

Finally, the ability to simulate solar air conditioning systems to a detail sufficient to optimize design and operating conditions is available today for both the solar powered and the solar related methods. This ability allows in-depth understanding of the system implications of combining solar energy and conventional technology into a workable solution for reduced fossil fuel dependence.

5.2 POTENTIAL DISADVANTAGES

Common design practice for solar energy space heating systems which have the storage subsystem in the building being heated is to ignore heat loss from storage and transport loops. This is because the energy loss is assumed to offset a portion of the heating load requirement. In hot water only systems such losses must be considered in evaluation of the solar energy system design as they represent inefficiencies of conversion of collected energy into its intended purpose. Air conditioning with solar energy has an even more severe problem with storage and transport losses. When attempting to satisfy a space cooling load these losses are both a reduction in capability and an increase in required load. This double

penalty means that greater care in design and greater cost in storage and transport subsystems are needed for solar powered air conditioning than for solar heating.

Both the absorption cycle and Rankine cycle/heat engine performs better at higher temperatures. Their operation at the upper thermal limits of most flat plate collector-water storage systems is not optimum. The increase in efficiency of the solar powered cooling equipment at higher temperature and the corresponding decrease in flat plate collector efficiency creates a system condition which compromises both. This conflict can be reduced by use of high performance collectors, high temperature storage techniques, and other specialized equipment. The limitation is that all of these improvements cost more than the basic system. There is a definite economic penalty to provide energy at higher temperatures. The closer to ambient conditions, the cheaper the energy.

Although methods exist to raise the operating temperature levels in the solar powered cooling systems, there are only limited benefits to be gained. Thermodynamic limitations on the systems and their basic technology are such that greatly increased efficiencies are not expected for the cooling techniques discussed. This is true regardless of future development efforts.

One basic thermodynamic limitation to higher temperature operation is collector heat loss. Collectors are able to convert only a portion of the solar energy that they receive into useful heat. This ability (or efficiency) is related to the heat loss from the collector due to temperature difference between the collector and its surroundings. The greater the temperature difference, the greater the loss. The higher the operating temperature level, the greater the difference, and the less efficient is the collector. Improvements in collector design (such as evacuated tube collectors) can reduce this effect but these have had a higher cost/performance ratio than good flat plate collectors.

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Most economically optimized solar powered air conditioning systems do not have the capacity to meet the entire cooling load. The comparative inefficiency of absorption cycle coolers operating in the auxiliary (non-solar powered) mode versus conventional electrical powered coolers is a serious drawback for economic residential utilization of absorption cycle techniques.

All solar powered air condition systems represent a new concept for the HVAC industry. As such, rapid acceptance should not be expected. Further resistance to acceptance is the general lack of commercially available "offthe-shelf" hardware. Thus, even if a typical engineer, architect, or homebuilder desired to include solar air conditioning in a structure the required equipment would not be found in their normal distribution and supply outlets. The National Demonstration Plan is expected to reduce this barrier, but it still exists today.

Increased complexity of the solar air conditioning system versus the conventional system and the decreased reliability associated with newly developed equipment indicates more frequent servicing of a more technical (and costly) nature would be expected.

An outdoor tower is required when water is used for cooling. The LiBr-H₂O and lower temperature NH₃-H₂O absorption cycles must have water cooling to operate. Although the Rankine cycle/heat engine concepts reviewed do not all require a cooling tower as such, the ones which showed greatest promise either did or else had a similar approach. Example of the latter was a system using an evaporative condenser. This concept requires ducting of ambient air over the condenser of the Rankine cycle and providing cooling by evaporation of water sprayed on the condenser coils. The performance is the same as for the cooling tower, but Cost-Trade studies indicate a possible improvement over the cooling tower approach.

Residential applications of absorption units have been shown to be generally economically unfeasible for solar energy systems. The near term prospects of the Rankine cycle/heat pump do not indicate that it will be economically competitive either. The general conclusion is that these solar powered techniques have an unfavorable cost/performance ratio when compared to conventional electrical powered air conditioners under near term economic conditions.

Both the Rankine cycle and the heat pump use fluoro-carbons (such as Freon) for working fluid. Increasing environmental concerns over release of fluoro-carbons into the atmosphere (through leaks, etc.) could prove to be a limitation to these systems as they are now designed.

The high cost of solar air conditioning equipment and the sensitivity of its performance to operating conditions place critical importance on load management. This importance indicates the need for well engineered control systems controlling well understood equipment.

Although existing detailed simulation techniques exist which can provide analysis of each of the cooling methods discussed, the computational cost of such simulation is significant.

5.3 TECHNOLOGICAL IMPROVEMENTS TREND

The general trend for solar air conditioning systems is to raise the overall operating temperature. This is accomplished by elevating solar heat supply temperature by either using larger collector arrays and reducing the collector loop flow rates or by higher technology collectors.

The high penalty of auxiliary mode fuel cost for absorption cycle systems is the main driver for the heat engine/Rankine cycle. This is because the auxiliary mode for the latter is identical to conventional cooling systems which can be 3 to 4 times as efficient as the absorption cycle.

In all cases described, start up conditions are less efficient than steady state. Greater efficiency is also found when the available energy is used when collected rather than stored and used later. These conditions are met by using cold storage to accept excess capacity and off peak operation of the cooling units. The latter is primarily useful for the heat pump system.

Proposed improvements for solar heat pumps have included development of higher efficiency by using variable speed and compression ratio, larger heat exchangers, and more efficient motors and compressors.

Even with all the proposed technological changes, practicality dictates that the expected big improvements in solar air conditioning will first be seen in increased system reliability. Later developments are expected to show increased efficiency.

The single greatest near term improvement from a technological and economic viewpoint is the encouragement of heat pump manufacturers to commercially produce a dual source residential heat pump. The technology is there. What is needed is for it to be done as soon as possible.

APPENDIX

SOLAR ENERGY AIR CONDITIONING
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