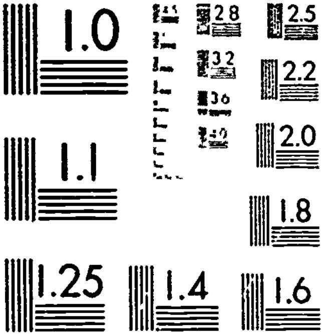

MICROCOPY RESOLUTION TEST CHART

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ABSTRACT

A consensus has developed among U.S. solar researchers that the solar-powered cooling of buildings is an important topic. Most solar heating systems are technically simple, and more highly developed, than solar cooling devices are. The determination of the best design concept for any particular application is not a simple process. Significant problems remain in the understanding of mechanisms, in the design and operation of cost-effective hardware, and in the understanding of the economic performance that is possible. Because of these remaining research ad development problems, many different concepts were explored at the workshop. In addition to the purely technical problems, there are problems of reconciling novel equipment with current buildings and with building practices, with other present-day hardware, with engineering, architectural, and building trade practices, with code and other legal requirements, with financial practices and taxation systems, with consumer esthetic and practical needs, and with a myriad of other such "non-engineering" interfaces. A specific session on "implementation" was devoted to discussion of obstacles facing solar cooling, with the participation of specialists in many of the nonengineering areas. (Author/MLF)

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Workshop Proceedings

SOLAR COOLING FOR BUILDINGS

February 6-8, 1974
Los Angeles, California

HELD IN CONJUNCTION WITH
THE
SEMI-ANNUAL MEETING OF THE
AMERICAN SOCIETY OF
HEATING, REFRIGERATING AND
AIR-CONDITIONING ENGINEERS
(ASHRAE)

PREPARED FOR THE
NATIONAL SCIENCE FOUNDATION
RESEARCH APPLIED TO NATIONAL
NEEDS
(NSF-RANN)

BY THE
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

PROCEEDINGS EDITED BY
FRANCIS de WINTER
WORKSHOP COORDINATOR

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Arranging the Workshop, on a fairly short notice, in conjunction with the Semi-Annual ASHRAE Meeting could not have been accomplished without the enthusiasm and assistance of Miss Julia Szabo, Dr. Joseph Cuba, and many other ASHRAE officers and members. Messrs. Harold Horowitz and Sidney Sternberg of the NSF gave continuing assistance in molding the program and finding speakers. Mr. Richard Schoen of UCLA assisted in developing the program format, particularly of the Technology Implementation Session, and Mrs. Frances T. Vargas patiently typed the manuscript through a number of editing iterations.

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SUMMARY SESSION

INTRODUCTION

The Workshop on Solar Cooling for Buildings was held at the Los Angeles Hilton Hotel in Los Angeles, California February 6-8, 1974. It was held in conjunction with the Semi-Annual Meeting of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), which had occuppied most of the earlier part of the week.

In the past year or so, a consensus has developed among U.S. solar researchers that the solar-powered cooling of buildings is an important topic. Solar energy collection systems tend to be expensive; and a solar heating system for buildings can become a much more attractive proposition if a solar cooling system can keep the collector working during a larger fraction of the year (Current thinking in this economic area is discussed in more detail in the paper on cooling of Löf in these proceedings.)

Most solar heating systems are technically simpler, and more highly developed, than solar cooling devices. A solar cooling system needs some sort of heat engine coupled to a heat pump, or some other combination of Second Law devices, to produce a temperature depression. Many such heat engines, heat pumps or other devices have been proposed or developed over the past two or three centuries, but the determination of the best design concept for any particular application is by no means a simple process. Significant problems remain in the understanding of mechanisms, in the design and operation of cost-effective hardware, and in the understanding of the economic performance which is possible. Because of these remaining research and development problems, many different concepts were explored at the Workshop.

In addition to the purely technical problems, there are problems of reconciling novel equipment with current buildings and with building practices, with other present day hardware, with engineering, architectural and building trade practices, with codes and other legal requirements, with financial (lending) practices and taxation systems, with consumer esthetic and practical needs, and with a myriad of other such "non-engineering" interfaces. A specific session on "implementation" was devoted to discussion of obstacles facing solar cooling, with the participation of specialists in many of the non-engineering areas.

To make the meeting as realistic and productive as possible, it was planned in conjunction with the ASHRAE Semi-Annual Meeting. This seemed likely to ensure the presence, contributions, and criticism of those who would ultimately have to use the equipment being studied. ASHRAE management supplied much enthusiasm and cooperation to make this idea successful.

The formal participants in the Workshop were chosen based on NSF requests, and on recommendations made by many people before the time of the meeting. The session schedules were arranged so that there was a significant amount of time which could be devoted to discussion of the presentations or to other comments, and these discussion sessions are documented in full at the end of each session.

Often a significant amount of time is spent answering a number of questions which could easily have been framed into a single one. Many questions are based on simple communication gaps or on lack of understanding. To limit as much as possible, the time spent in overcoming such problems, the audience was asked to use written question forms for the most important questions. These forms were then supplied to a "Commentator," who was given a chance to organize them during a coffee break between the presentations and the questions and answer session. The commentators were chosen among people who were deemed likely to be able to contribute significantly to the discussion, and were also supplied with such prior handout material as the formal speakers could make available.

No written material was required prior to the meeting, although some speakers did supply written versions of their presentations at a later date. The presentations, and the question and answer sessions were taped at the time of the meeting. Typed transcripts were subjected to preliminary editing and then retyped. The speaker then did such editing as necessary, and the masters were produced for the proceedings.

A central bibliography was assembled for the proceedings. In addition to the references quoted by the participants, it was attempted to include enough other references to make it useful to those entering the field.

The proceedings were prepared and published at the Jet Propulsion Laboratory under Grant No. AG-502 from the National Science Foundation. The contents of the papers and the opinions expressed in the discussions are those of the participants and do not necessarily reflect the views of the Jet Propulsion Laboratory or of the National Science Foundation.

OPENING SESSION - OVERVIEW PRESENTATIONS

Session Chairman: Lloyd Herwig

SOLAR ENERGY TECHNOLOGY CHAPTER IN ASHRAE HANDBOOK

John I. Yellott
ASHRAE And Arizona State University

The chapter itself originated as a manuscript of some 80 pages, destined for publication in the 1974 ASHRAE Handbook of Applications. The ASHRAE Handbooks constitute the bibles on which the air conditioning profession depends for its technical knowledge. One of the most useful portions of the 1972 edition is Chapter 22 which deals with solar heat gains through fenestration. That chapter was the responsibility of Technical Committee TC 4.5, Fenestration. I have had the privilege of serving on that Committee since 1963 and it was my first introduction to writing for the ASHRAE Handbook. ASHRAE produces one of these each year, and the 1974 Handbook of Applications will contain the complete chapter dealing with the use of solar energy for heating and cooling. The second half of the chapter has already appeared in the December, 1973, issue of the ASHRAE Journal. The first half of the chapter contains more of the technical details which will be of real importance to those of you who have to design solar systems.

Fortunately, a tremendous amount of technology is already available, much of which appears in ASHRAE publications. Going back 15 or 20 years, you will find some very fine publications, notably those of Jordan and Liu from Minnesota, Farber and Pennington from the University of Florida, and Daniels and Duffie from Wisconsin. The exact title of the chapter under discussion is "Utilization of Sun and Sky Radiation for Heating and Cooling of Buildings." I was selected to write this chapter because I was chairman of TC 6.7, Solar Energy Utilization.

The use of the sun for the heating of buildings is not a new concept, but the use of the sun for cooling is in large measure new technology and that is why you have gathered here. In the part of the chapter which will not be in print until late in June, there is first a brief summary of prior art. There were many early contributors to solar energy technology starting with the late Charles Abbot and including the team at the University of Wisconsin started by Daniels and ably carried on by Jack Duffie (Daniels and Duffie, 1955), the pioneering work of Hottel and Whillier (1955) at MIT, George Löf (1963), Maria Telkes (1949), and Mr. and Mrs. Raymond Bliss (1955). The Bliss home in Amado was one of the first buildings in the world to be cooled by nocturnal radiation and heated by solar energy. Unfortunately, it stood in the way of progress and was torn down as was the solar laboratory (Bliss, 1961) which they later designed and built for the University of Arizona in Tucson. This stood on land later needed for the University's Medical School and so it too was demolished.

The Bridgers and Paxton (1957) office building in Albuquerque was the first in the U.S. to combine solar collectors and the heat pump. With the assistance of NSF, the solar collectors are about to be brought back to life again and reinstrumented. Harry Thomason's (1960) three solar-heated homes in Washington, D.C. must not be overlooked, and Erich Farber is here to talk to you about the University of Florida's work (Farber and Morrison, 1973). We also have here a member of the team from the University of Delaware, Kudret Selçuk, who was on the Solar One project from its inception.

The first thing that I tried to do when I began putting the chapter together was to get a table of probable values of clear day solar radiation for various latitudes and various dates in the year, comparable to the Solar Heat Gain Factor tables which appear in the 1972 ASHRAE Handbook. I asked Professors Morrison and Farber at the University of Florida to change their Fortran program to make it print out values of actual solar intensities rather than Solar Heat Gain Factors and they have compiled a series of tables using the most reliable data now available.

Back in the 1940's Moon's (1940) value of 419 Btu/hr/ft^2 was the officially accepted value of the solar constant and nobody has yet improved very much upon Moon's values of the solar spectral distribution on the surface of the earth. Abbot's value of 429 Btu/hr/ft^2 (Abbot et al, 1923) was his final estimate of the solar constant after 50 years of work for the Smithsonian. When NASA-JPL and Thekaekara (1973) and their co-workers finished their high altitude tests they concluded that 429.2 Btu/hr/ft^2 was the most probably value of the solar constant. I know that Abbot prized very highly the fact that their values measured at the very edge of the earth's atmosphere agreed almost exactly with his.

Thekaekara has also verified Abbot's findings that there are very small but measurable variations in the solar constant itself, varying with the sun spot cycle. The Johnson value of the solar constant, 445 Btu/hr/ft^2, is definitely too high, and the NASA-JPL figures which are given in great detail by Thekaekara (1973) in a number of publications, are the ones which ASHRAE will be using for the foreseeable future.

We must know the solar altitude and azimuth angles so we can tell at what angle the sun's rays will hit collectors. The solar declination must also be known and for that there is a readily available source of information: the "Old Farmers' Almanac" (Thomas, 1974). Solar altitude formerly had to be calculated, but now you can read it out of the University of Florida's tables and from the 1972 ASHRAE Handbook (pp. 388-92). Solar time is a tricky business now, because everywhere else in the United States other than Arizona and Hawaii, you must consider daylight saving time all year-round and that can throw you off by an hour. The actual distribution of the solar spectrum, as shown in Figure 1, is something with which people in the space program are vitally concerned. We who are literally more mundane in our interests need to know primarily what is the actual intensity here on the surface of the earth. The major significance of the terrestrial solar spectrum is to show you where the absorption bands are and what actually reduces the intensity of the solar radiation.

In the chapter, there will be a tabulation for 40 degrees north latitude of the sun's altitude and azimuth and direct normal irradiation intensity on typical clear days on the 21st day of each month. The total insolation is also given for horizontal surfaces and for surfaces which are tilted at the latitude -10°, the latitude, latitude +10° and latitude +20°, and 90°. Similar data are readily available for latitudes from 24° to 64°, by 8° increments. If you insist upon calculating them, the Fortran program is relatively simple but now with these Univ. of Florida tables available, I think that people will be just as happy to interpolate because the differences are relatively small.

Figure 2 shows you what the insolation picture looks like on the 21st day of July at 40 degrees north latitude for a south-facing surface which is tilted at 40° from the horizontal. There are two primary things to notice. One is that you reach a maximum insolation of something like 300 Btu/hr/ft^2 at the middle of the day on a surface which is facing due south. The other important consideration is the variation of the angle of incidence, which starts off extremely high in the morning, and that is one reason why solar collector efficiencies are low in the early morning. The incident angle gets down to its minimum at noon and increases again in the afternoon.

The data for making similar charts are now available if you are interested in some other latitude than 40 degrees north. 40 degrees is approximately the latitude of Philadelphia, Pittsburgh, Denver and other interesting places but not Phoenix or Los Angeles. Most days of the year are clear in Phoenix but that is not the case everywhere and so there are corrections called Clearness Numbers which are built into the ASHRAE procedure. In the 1972 handbook and again in the chapter is the map shown in Figure 3 which shows by dashed lines the Clearness Numbers which apply to various parts of the United States.

If you live close to the Gulf states and Florida you will have a somewhat lower intensity on a clear day than if you live in Denver or Albuquerque or some other location where you are a mile high. The clear day data are there primarily for design purposes; the real difficulty comes in trying to find out through the Weather Bureau, which I should now call NOAA, exactly what you're likely to have in the way of clearness for a prolonged period of time so you can make a realistic estimate of the total amount of energy that you are likely to be able to collect.

Let's turn for now to the technology of solar energy utilization, which is discussed in the December, 1973, issue of the ASHRAE Journal. I did not deal with the helio-electric or helio-chemical processes because they were not part of my assignment. The December article, which is actually the second half of the chapter, deals with domestic hot water heating, space heating and cooling. I will say very little about cooling today because this subject is being adequately covered by other speakers. There are at least three ways in which cooling can be accomplished. Nocturnal radiation and evaporative cooling have had their usefullness proven over a period of 18 months at an experimental Skytherm building in Phoenix. Absorption refrigeration is going to be the subject of a great deal of discussion here, and this is even older than Abel Pifre's printing press in Paris in the 1870's.

Figure 4 shows some of the heater types with which most of you are familiar. The thermosyphon is the one which is most widely used, and there used to be hundreds of them in Southern California and Arizona until natural gas and electricity became available. Then people scrapped their solar heaters and bought the much less expensive fuel-burning units. Now builders in my part of the country are saying, "What ever happened to those solar heaters you were telling us about 15 years ago? We find we can't buy natural gas for our new houses." The answer is that the thermosyphon heater, the forced circulation heater and Harold Hay's simple skytherm system of an open roof with moveable insulation are going to come into their own, because the economics are going to be extremely favorable in the future.

The gravity system of Harry Thomason is indicated in the upper right hand corner of Fig. 4. Concentrators of various kinds have been studied by many people. The problem with the concentrator is that it can only use the direct rays of the sun, and you have to provide some means to make it follow the sun. You can heat air as well as liquids and the diagram in the lower right hand corner shows a very simple kind of air heater using the cheapest kind of corrugated barn roof aluminum which works remarkably well in our part of the country. I saw similar systems working in the houses near the French solar furnace in the Pyrenees and it appears to me that this has valuable possibilities for very low-cost applications.

We must bear in mind the behavior of collectors, because they have rules of their own, and there is not very much that we can do about them. First of all, we have to put a glazing over our collector if we want to get satisfactory efficiency out of it, and the transmittance of the glazing is going to vary with the incident angle. As the angle of incidence of the sun's rays on the glass begins to rise, the ability of the glass to transmit solar radiation drops down and finally when you get up 90 degrees no sunshine enters at all. An absorbing surface does much the same thing. It absorbs very well at low angles of incidence, but at high angles its absorptance drops off also. When you multiply the transmittance by the absorptance, the effect is compounded and the higher the incident angle rises, the lower is your collection efficiency. Also, as the temperature rise of the collector surface above the ambient air goes up, the efficiency of the collector goes down.

Finally you reach an equilibrium temperature which is the temperature that the collector attains when you don't take any heat away from it and simply allow it to lose whatever heat nature will take away. Ordinary flat black heaters will reach temperatures well above 200 degrees if they have a single cover glass over them. Selective surfaces with high absorptance and low emittance will get much hotter than that, and there are some very special kinds of collectors which are being developed now, which have some very interesting possibilities.

We know how to store heat, Fig. 5, in the form of hot or cold water by simply putting it into insulated tanks and pumping it out when we need it. We know how to store heat or cold in rock piles. The Australians are doing this very effectively and I hope that we are going to bring some of their technology into the United States very soon. Maria Telkes and others are working along diligently with eutectic salts. Maria Telkes is now encapsulating her materials in long slim tubes similar in size to flourescent lamps so that they can overcome the fact that when they freeze, the frozen portion sinks to the bottom. Most liquids have the unhappy habit of having their solid constituents sink when they freeze.

Figure 6 shows a typical system for heating and cooling and you will notice what appears to be a heating system. I have shown a collector, a storage system, some way to distribute the stored fluid, an auxiliary device of uncertain and undetermined nature and a little word which says cooling. If the water is hot enough, you might use an absorption system; if not, I do not know what you will use. That's where I am about to leave you, but I'm going to give you a clue. If you really want to know about the early absorption systems, see whether in some antique book shop you can get a copy of Modern Electric and Gas Refrigeration by Althouse and Turnquist (1944) published by Goodhart and Wilcox in Chicago in 1944. This has beautiful pictures of the Servel Electrolux, the Faraday Refrigerator and all of the other absorption systems.

If you want to know how the earlier absorption systems actually worked, get a copy of this book and take a look at it. I end with this interesting little historical note. The discovery of ammonia and absorption refrigeration took place simultaneously in 1824 by Michael Faraday, who was trying to make liquid ammonia. Nobody had ever made liquid ammonia prior to 1824. There was plenty of gaseous ammonia available and he found that silver chloride had the property of absorbing large quantities of ammonia. So he made himself a double-ended test tube such as shown in Figure 7 and he put a burner under the silver chloride which had become saturated with ammonia. When he heated the silver chloride, the ammonia gas was driven off and condensed in the right hand side of his apparatus. Then he turned off the burner and went away to do something else.

When he came back, much to his surprise, he found that the right side was covered with ice. What had happened was that the ammonia which had been turned into liquid had reevaporated and absorbed all the heat it could possibly pull from the atmosphere. The NH3 had been reabsorbed back in the silver chloride and that was the first absorption refrigerating system. There was a company called the Faraday Refrigerator Company and they were the ones who prepared Figure 7. I think they are now defunct, but if anybody can dig up one of these, it certainly ought to be in the Smithsonian because it was the most ingeniously-designed device. I have now come to all that I know about absorption refrigeration and this is the proper time, I think, for me to draw my part of the program to a close.

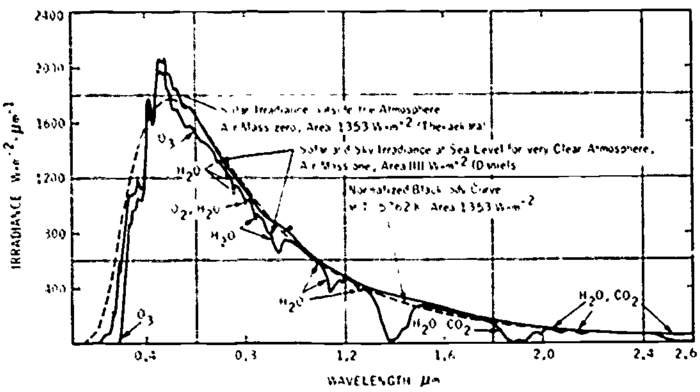
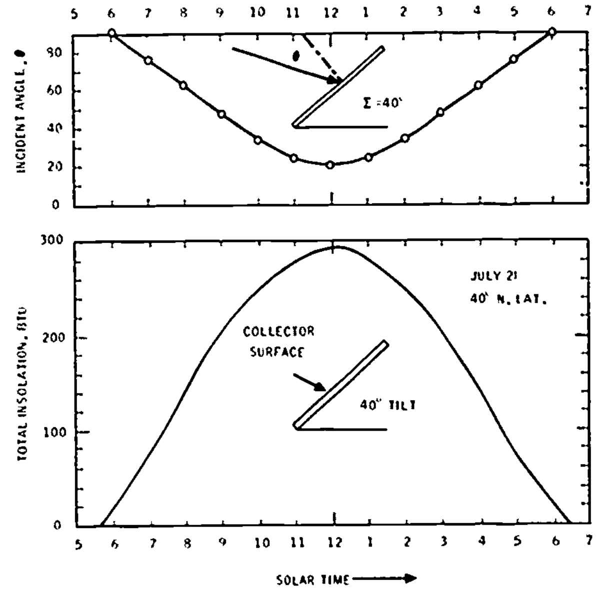


Fig. 1. Solar Spectrum at Air Mass 0 and 1 (Courtesy of M. P. Thekaekara, Goddard Space Flight Center, NASA).

Fig. 2. Insolation on July 21 at 40° Latitude for Surface Tilted at the Latitude Angle.



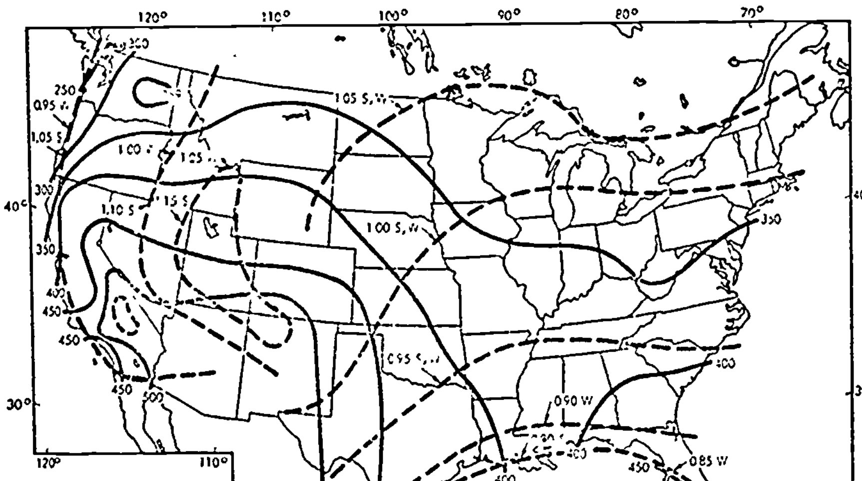


Fig. 3. Annual Mean Daily Insolation (solid lines) in Langleys, and Summer and Winter Clearness Numbers (broken lines) Plotted on a U. S. Map. Illustration courtesy of H. P. A. C.

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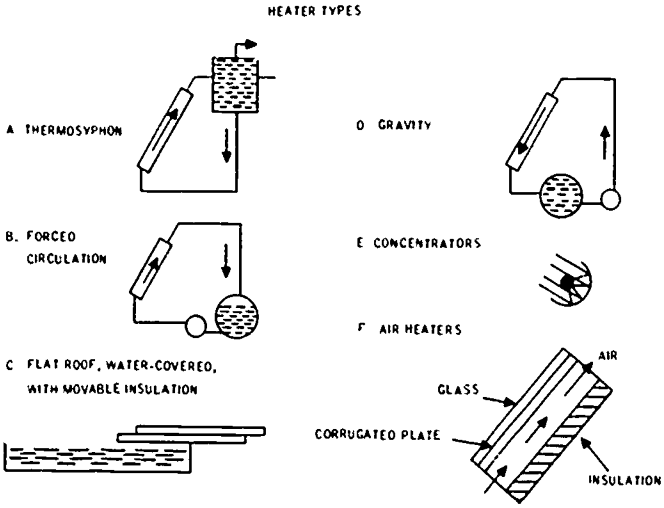

Fig. 4. Typical Solar Heat Collectors.

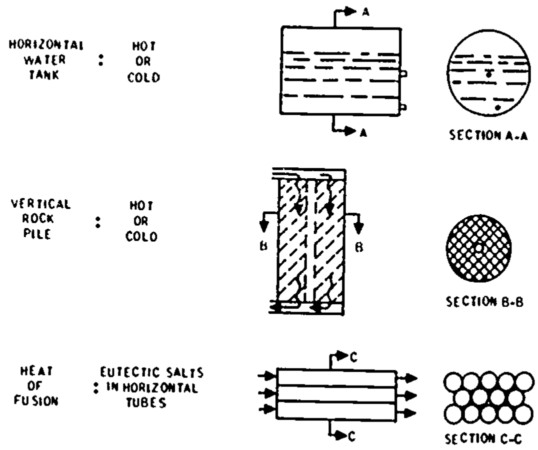

Fig. 5. Various Heat Storage Concepts.

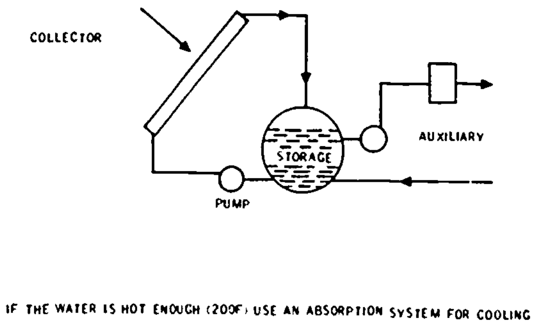

Fig. 6. Typical Water Heating System.

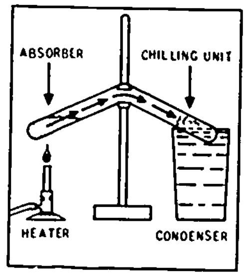

Fig. 7. Original Faraday Absorbtion Refrigerator.

OVERVIEW OF NSF ENERGY PROGRAMS

Harold Horowitz

NSF

I will present a brief survey of all of the energy activities of the National Science Foundation. At this time that is a very difficult thing to do because we're again at one of our transitional stages and expect to grow in a very significant way in fiscal year FY 1975. The following description of the energy programs of the Foundation, is in the context of what is likely to happen rather than what has been doing in the past. On Monday of this week, a news release was issued about the FY'75 budget statement which is part of the budget that the President has submitted to the Congress. The 1975 budget for the National Science Foundation requests major increases for the support of research directed towards acquiring knowledge needed to help solve problems of national concern, with very special emphasis on energy.

First let me pause from the main part of this talk and answer questions that are often asked by ASHRAE members who may not have previous exposure to the National Science Foundation. NSF is a federal agency, one of the independent agencies, and receives its funds through the familiar process of Congressional authorization and appropriation and finally through the Office of Management and Budget. The broad agency goals of the National Science Foundation are to increase scientific knowledge and to improve U.S. scientific and engineering strength in order to assure that adequate fundamental understanding and capability are available for national purposes. These goals were the dominant objectives at NSF for many years. More recently added are additional objectives which include discovering and proving the feasibility of new and innovative applications of science and technology to selected problems of the civilian sector, and to identify and develop methods to encourage the use of science and technology by all types of organizations throughout our society.

The budget request for FY'75 totals $788,000,000. and that represents $142,000,000. above the estimated program level for FY'74 which is $646,000,000. Out of this requested increase of 141.8 million dollars, almost all is earmarked for energy research. That is, 1.379 hundred million dollars of the increases are earmarked for energy research.

The National Science Foundation is organized into several major structural components or directorates,--the Assistant Director for Research Applications often called RANN, Research Applied to National Needs; the Assistant Director for Education; the Assistant Director for National and International Programs;ithe Assistant Director for Research, the oldest part of NSF; and the Assistant Director for Administration. Nearly all of the energy related funding that we anticipate at the National Science Foundation in the next fiscal year will be concentrated in two of these Directorates. Research will have the largest amount of funds which are energy related, and that comes to $131,000,000; and RANN has requested $103,000,000 for energy related research. There is some additional money distributed through the other Directorates. $252,000,000 out of a total for NSF of $788,000,000, is for energy related activities, so about 1/3 of NSF's total program will be energy related in the next fiscal year.

Now, let me tell you something about the specifics of these activities. Under the Assistant Director for Research, are a number of divisions. A substantial number will have some energy related research. For example, the Division of Mathematical and Physical Sciences will do research in physics that is related to energy conservation and storage. The Division of Social Sciences will be concerned with analysis of energy related problems in the social sciences, international economics research dealing with linkages between national economics, and methods to include these linkages in international econometric models. Within the Division of Engineering, attention is going to be paid to innovations that can reduce or bypass high energy consuming steps in chemical reaction systems. They will be supporting heat transfer research as well. Another Research Division, the Division of Materials Research, will be supporting basic studies that can lead to improvements in superconductors, improvements in the materials that are used for photovoltaic cells, and also, will be trying to find materials which can improve high temperature performance of turbines and of coal conversion plants.

The principal emphasis of the Directorate for Applied Research (RANN) is in three major problem areas--energy, the environment, and productivity. The Division of Advanced Energy Research and Technology of RANN will have in its program for FY'75 a major research effort to find ways to make practical applications of solar energy and geothermal energy. This includes programs designed to develop other nonconventional energy sources such as wind energy and ocean thermal gradients. Also, it will be trying to find more efficient ways to utilize conventional energy resources such as coal, and shale deposits, and support system analysis to assess alternative energy systems and public policy options. It will also be working in energy conversion and storage, energy and fuel transportation, and attempting to increase engine fuel economy and cycle efficiency. Another division of RANN, the Division of Environmental Systems and Resources will attempt to understand more about the environmental effects of energy utilization.

Two programs in the Education Directorate should also be mentioned. One is for improving technician education in the energy field, and the other will support visiting scholars to the United States in the energy field.

OVERVIEW OF NSF SOLAR ENERGY PROGRAM

Lloyd Herwig

NSF

I would like to take the next period of time to tell you about the solar energy program at the NSF, and for the Federal government as a whole. I will begin by reminding you about some of the characteristics of the solar energy resource. The amount of solar energy falling on the United States in a year's time is about 700 times our present rate of energy consumption. Put another way, the average daily solar energy arriving on about 5,000 square miles of United States territory is about equal to our total energy use.

Our daily total energy use, of course, requires conversion of many types of fuels for a wide variety of needs. As we proceed, I will point out that technically feasible solar energy conversion methods can produce many forms of power and energy. For example, high and low temperature thermal energy; electricity; and, gaseous, liquid, and solid fuels.

It is significant to note that the solar energy falling in a year on a square foot of average land or roof in the continental United States has a value of about $1 based on energy unit value of $2 per million BTU. This is based upon the average United States insolation of 1480 BTU's per square foot per day (4000 kilocalories per square meter per day). As you know however, the value of 1,000,000 BTU's is very much a function of the temperature at which it can be delivered, the purposes for which it is to be used, and where it is to be delivered.

Solar Energy has numerous advantages as an energy source. The sun is a large continuing source of domestically available energy, it is widely distributed, and its use does not add to the earth's overall heat inventory.

The wide distribution of solar energy over the United States makes it possible to consider systems providing thermal energy or power at the point of use without recourse to the extensive distribution networks required with central power stations.

Next, consider two major disadvantages of solar energy that pose challenges to innovators in research and technology. Sunlight intensity is relatively low presenting a technological challenge to achieve its economic conversion to more useful forms of energy. Solar energy is intermittent and variable due to diurnal, seasonal, and environmental obscuration effects. Thus the energy must be either used as it becomes available, or used in conjunction with storage and backup systems. Because of these two disadvantages, there are requirements for large collector areas, and some energy storage. This in turn gives rise to higher initial capital cost than many competing technologies.

In considering the cost competitiveness of solar energy systems, however, one needs to take into account life cycle costs including fuel and impact costs, in addition to the initial cost. As a result of research and technology projects underway, we believe by the early 1980's some solar energy systems can meet the challenge of producing substantial quantities of energy at acceptable commercial costs based upon cost accounting that takes the system's life cycle costs into consideration. Further, other approaches to producing power from solar energy systems can be implemented by the late 1980's.

The general characteristics of the solar energy system being developed in the National Solar Energy Program are as follows: No insurmountable technical barriers to their implementation, numerous conversion methods, and promise of cost competitiveness. Solar energy systems moreover would conserve domestic fossil fuels, create new exportable technology projects, and thus improve the balance of trade picture. Additionally, solar energy has minimum environmental impacts.

In April, 1973 the National Science Foundation was designated by the President's office to be the lead federal agency in planning and coordinating the broad area of solar energy research and technology. Five-year program plans for research in each of six selected solar energy technologies have been developed and are reviewed and revised periodically. The plans and policies of the National Solar Energy Program are focused on the general objective of developing at the earliest feasible time those applications of solar energy that can be made economically attractive and environmentally acceptable as alternative energy sources. The program plans are adjusted to reflect continuing critical reviews based on new information and understanding, assessment of priorities, identification of research and technology needs, levels of funding, and research capabilities. An integrated research plan recognizing the multi-disciplinary nature of solar research is being implemented with an estimated NSF funding of 13.2 million dollars in FY'74.

The general objectives of the solar energy program are stated in the following way. To provide the research and technology base required for economic terrestrial applications for solar energy. To foster the implementation of practical systems to the state required for commercial utilization and to provide a firm technical, environmental, social and economic basis for evaluating the role of solar energy utilization in US energy planning.

The research and technology activities for the national solar energy program are organized under the following six areas. Heating and cooling of buildings, solar thermal energy conversion, photovoltaic conversion, biomass production and conversion, wind energy conversion, and ocean thermal energy conversion. The NSF budgets for solar energy applications in past years and for the current year are shown in Figure 1 for each of the six program areas. The budgets are given

NSF/RANN SOLAR ENERGY BUDGET
(Millions of Dollars)

	FY 1971 (Actual)	FY 1972 (Actual)	FY 1973 (Actual)	FY 1974 (Estimate)	FY 1975 (Request)
SOLAR ENERGY FOR BUILDINGS	$ 0.54	$ 0.10	$ 0.40	$ 5.9	$ 17.0
SOLAR THERMAL CONVERSION	0.06	0.55	1.43	2.2	10.0
PHOTOVOLTAIC CONVERSION		0.33	0.79	2.4	8.0
BIOCONVERSION FOR FUELS	0.60	0.35	0.65	1.0	5.0
WIND CONVERSION			0.20	1.0	7.0
OCEAN THERMAL DIFFERENCE CONVERSION		0.14	0.23	0.7	3.0
WORKSHOPS AND PROGRAM ASSISTANCE		0.19	0.26		
	$ 1.20	$ 1.66	$ 3.96	$ 13.2	$ 50.0

Figure 1

in terms of Federal fiscal years. The NSF solar energy budget shows $1.2 million in FY'71, $1.66 in FY'72, $3.96 in FY'73, $13.2 (estimated) in FY'74 and $50 million (estimated) in FY'75. It should be made clear that the estimated budget in FY 1975 is a requested budget that is subject to the decision of Congress. The relatively large percentage increases in total funding are very apparent over the period from FY'71 to the present. In particular, the increases are more than a factor of three from FY'73 to FY'74 and FY'74 to FY'75, showing the growing federal interest in exploring solar energy alternatives.

The total FY'74 Federal funding of solar energy research and technology performed outside federal laboratories is estimated at 15.1 million. Five federal agencies are considering some funding for FY'74. The NSF has 13.2, NASA .9 million, the AEC about .6 million, the Department of Defense has about .2 million and the US Postal Service has .2 million. In addition, there are Federal inhouse research and technology projects that add to the Federal total funding.

The NSF planning for implementing solar energy applications emphasizes a phased project planning approach embodying integrated programs of multidisciplinary research, analysis, experiments, and system studies. The most important steps in phased project planning leading to new applications are shown in Figure 2. The research phase can include basic and applied research

STEPS IN PHASED PROJECT PLANNING TO DEVELOP A NEW APPLICATION

NSF	RESEARCH PHASE		ANALYSIS AND TEST OF NEW PROCEDURES INTERDISCIPLINARY RESEARCH AND SYSTEMS ANALYSIS. RESEARCH ON MATERIALS, COMPONENTS, AND SUBSYSTEMS
	*********************		
NSF	PHASE 0	POCE	CONCEPTUAL DESIGN AND REQUIREMENTS SPECIFICATION. ECONOMIC ANALYSIS AND IMPACT ASSESSMENT RESEARCH ON CRITICAL MATERIALS, COMPONENTS, AND SUBSYSTEMS.
NSF	PHASE 1	POCE	PRELIMINARY SYSTEM DESIGN. CRITICAL SUBSYSTEM RESEARCH, DESIGN, AND TEST.
NSF	PHASE 2	POCE	DETAILED SYSTEM DESIGN SYSTEM CONSTRUCTION, TEST, AND EVALUATION
	*********************		
OTHER	PHASE 3		DEMONSTRATION SYSTEM DESIGN, CONSTRUCTION, AND OPERATION.
OTHER	PHASE 4		COMMERCIAL SYSTEM DESIGN, CONSTRUCTION, AND OPERATION.

Figure 2

on advanced approaches to solar energy conversion; feasibility studies; research and analysis on innovative ideas, materials, components, subsystems; and, basic data required for analysis. Proof-of-concept experiments (POCE's) are major milestones in the program plan. After a successful proof-of-concept experiment, the plan continues to the demonstration systems and commercial phases. A system proof-of-concept experiment is undertaken to prove that the full technology base is available to enable a user community to move into the design and development of an economically viable system. In each program area, these experiments are scheduled by FY 1978 to be either in the construction and test evaluation (Phase 2), the preliminary system design (Phrase 1), or the systems analysis and selection (Phase 0), if results in successive stages justify continuing. Subsystem proof-of-concept experiments are programmed as soon as possible to verify the performance, life-time, and operational and environmental responses associated with materials, components, subsystems, and the general system.

I will highlight the current efforts with particular emphasis on the highest priority area which is solar energy systems for building. In our projections for advancement, in each of the areas of applications of solar energy we have system proof-of-concept experiments, to be completed into Phase 2 within five years in three areas-heating and cooling of buildings, wind energy conversion, and biomass production and conversion. In the other areas, solar thermal conversion, photovoltaic conversion, and ocean thermal conversion, component research and subsystem proof-of-concept experiments will be completed and Phase 0 and Phase 1 will be initiated on system proof-of-concept experiments.

It should be emphasized that no technological breakthroughs are required -though we expect some-to obtain useful energy and power from early versions of these solar energy systems. The major problem in each application area is to develop systems that are economically acceptable to the public and commercial sectors in the United States. To do this will require innovative engineering in conjunction with knowledge and understanding of nature's laws; improved approaches to collection and conversion of solar radiation, and advances in energy storage, transport, and conversion; new systems approaches; and, perhaps most importantly, new and cheaper materials to increase system performance, reliability, and economic acceptability. Important problems must also be solved dealing with other factors, e.g., social, legal, political, regulatory, environmental, and economic which are identified with wide spread implementation of solar energy systems.

A summary of objectives, technologies, and present projects for each of the six application areas will be described in the following sections. The general objective of the solar-energy-for-buildings area is to establish the widespread utilization of systems using solar energy for heating, cooling, and supplying hot water needs for buildings in the United States. This can be done of course, only to the degree that the system applications are economically viable, technically feasible, and socially acceptable. More specifically, the five-year objectives are to obtain increased performance and new options for components, subsystems and systems, and to complete proof-of-concept experiments through test of optimized experimental systems for a number of economically viable applications. The application of heating and cooling to buildings has the largest priority for funding in the current year's budget (FY 1974), about 45% of the total, because it is the solar energy area in the most advanced state of technology and economic viability. It offers, moreover, an excellent opportunity to make a significant impact on national energy requirements. At present, commercial and residential building uses account for approximately 25% of the energy consumed in the United States, at an annual cost of about 18 billion dollars. Solar energy systems for space and water heating in buildings have received experimental testing in the past, while combined heating and cooling systems have received very little experimental testing, even in the laboratory. Modest performance data is available for fewer than 25 solar heating systems constructed over the past 30 years over the entire world.

A conventional approach to a solar energy system providing heating and cooling for buildings will now be described. The sun's radiation is converted to heat by means of an absorbing surface incorporated in a flat plate collector assembly. The absorber surface has characteristics in common with many ordinary materials that get very warm in the sun. It is usually mounted in a structure that is designed to reduce direct heat losses by conduction, convection, and radiation. A heat transfer fluid is passed through channels in contact with or integral to the heat absorber surface. The fluid is circulated to a heat storage unit, or to the heating and cooling service systems, as required.

A common collector configuration consists of a coated black metal surface including heat transfer channels sandwiched between heat insulating structures. The sun side is insulated by a transparent structure consisting of one to three layers of infrared opaque glass (or plastic) each spaced about one half inch apart. This transparent structure is held about one half inch above the absorbing surface to reduce heat losses by convection and radiation.

The back side of the absorbing surface is covered by a thick layer of thermal insulation to minimize heat losses from the bottom of the collector. The collector performance may be improved by using selective coatings to maintain or increase the absorption of solar radiation at the absorbing surface while reducing the loss of energy by reradiation. Also transparent coatings or chemical treatments of the surface may be applied to the glass surfaces to reduce reflections of solar energy at air-glass interfaces. Variations in collector configurations and designs are being studied to increase energy collection efficiency and to increase output temperatures for some purposes. It is necessary to increase the quantity of energy collected, to reduce costs, to reduce material fabrication and operating cost, and to increase performance and lifetime. Collector design is one of the very important components in the cost of energy in a solar energy system.

You will be hearing much more about the absorption refrigeration system in the next few days. Therefore, I will not at this time talk about that system.

In September, an award of $238,000 was made to Colorado State University to design, construct, test, and evaluate an optimized solar heating and cooling system in a fully instrumented experimental house, near Fort Collins, Colorado. It will be the first full-scale optimized heating and cooling system test to provide 50 to 75% of the needs for climate conditioning and hot water heating. This project will provide important information on system performance, reliability of components and materials, system operational characteristics and maintenance problems, and accuracy of modeling calculations for these types of systems.

Three independent studies by industry-university teams were initiated by NSF in October as the initial phase (Phase 0) in systems proof-of-concept experiments for heating and cooling of buildings. These studies will be completed by June, 1974. They will identify the most viable applications of solar energy systems considering all types of buildings in all climatic regions of the United States. Mr. Raymond Fields will be discussing these studies later, along with the next two projects that I will only mention now as a part of this program area.

A mobile solar research laboratory is under construction with NSF support to test advanced equipment for the solar heating and cooling of buildings. This laboratory is to be housed in two trailer vehicles which will be moved to various locations in the United States to collect experimental data on systems performance under a wide variety of climatic and sun conditions. The climatic and insulation characteristics will be measured with installed equipment. Another purpose of the laboratory is to acquaint designers, architects, building contractors, zoning and building code officials, mortgage lenders and others with the characteristics and capabilities of solar energy heating and cooling systems for buildings.

In January the NSF initiated four projects called solar energy school heating augmentation experiments to advance the systems technology for using solar energy for space heating and hot water needs of buildings. A high school, two junior high schools, and an elementary school in different geographical areas and in different institutional settings are expected to augment their regular heating systems with different experimental solar energy systems to be installed by March.

In parallel with and in support of the proof-of-concept experiments, demonstrations of applications will be carried out by other organizations. The Department of Army, the General Services Administration, NASA, and the United States Postal Service have initiated phased projects that can lead to solar heating and cooling systems in their facilities. These programs, if completed, will become part of the program for proof-of-concept experiments and will provide important data points in the understanding of the problems of utilizing solar systems.

As proof-of-concept experiments proceed, a... and supporting research on new and improved components and systems will continue. The research projects conducted in the past have brought the state-of-the-art to the point that the present experiments can be done. The supporting research and technology will be programed for the future generations of heating and cooling systems as well as for the immediate needs of the proof-of-concept experiment. The advanced research and technology program will be oriented to innovative systems, subsystems, and components and to obtaining new options for increased performance and reducing the cost of systems. This work will result in technology for second and third generation systems that will if all goes well, reduce or eliminate the reliance of these systems on auxiliary power sources.

Many of you are familiar with the program solicitation that was placed in the late summer. The NSF asked for proposals in ten areas, and the proposals were requested by November 28. About 450 proposals were received. The evaluation panels have met, negotiations with the top-rated proposers have been initiated or will be initiated in the near future. Final decisions by a source selection board in funding of the projects will be completed in the next few months. We anticipate the order of 30 or more projects being funded out of that program solicitation.

There are now 27 active, research and study projects supported by about five million dollars in federal funds to non-federal institutions working on solar energy for buildings. These projects are supported by NSF (22), HUD (1), NASA-Lewis (1), AEC (1), Department of the Army (1), and the United States Postal Service (1). As I said, about 20 or 30 more projects will be initiated by NSF in FY'74. Research areas of greatest potential impact include improved collection of solar radiation, that is for higher temperatures and for higher efficiencies; improved heat transfer and transport systems, heat storage materials, and systems; space cooling systems to get higher efficiencies at practical solar system temperatures; and materials to get better and cheaper performance and combinations of functions. In each area of research need, it is imperative that costs of producing, installing, and maintaining the systems be reduced while maintaining or improving the system performance.

A technology assessment has been initiated with emphasis on the potential societal impacts of large-scale implementation of solar energy applications, with emphasis on solar energy systems in buildings. This study seeks to predict secondary and ternary impacts and problems to society, the economy, competitive industries, material resources, material dislocations, and new large-scale industries.

I would like now to pass to the second area that the solar energy program includes which is solar thermal conversion. The general objective is to prove the technical and economic feasibility of solar thermal conversion systems providing electrical or combined electrical and thermal service. More specifically, the five-year objectives are to complete system studies to select sites and systems for proof-of-concept experiments and to complete subsystem proof-of-concept experiments on solar concentrators and collectors, thermal collection and transfer, energy storage, heat exchangers and organic Rankine energy conversion cycles. The NSF also has initiated a number of projects to try to optimize the economics of solar thermal systems. Federal funding in this research area is estimated to be about $2.4 million dollars in FY 1974 including $2.2 million from NSF and $200,000 from NASA. Systems studies and analytical modeling to optimize system performance and power costs are underway along with collector-concentrator experimental studies, selective coatings, experimental studies, mission analysis, and design and experiments on other system components.

Solar thermal conversion systems collect solar radiation and convert it to relatively high temperature heat that can be applied to a boiler in a conventional thermodynamic cycle to produce electricity or mechanical shaft power. The steam raised by applying heat to the boiler can also be used to produce process steam or water for manufacturing or heating needs. For the sake of higher conversion efficiency and thermodynamic cycles, it is desirable to collect heat at as high a temperature as possible.

Several different system approaches are being studied for concentration of solar energy. In the first approach, generically referred to as distributed radiation collection, large parabolic cylindrical mirrors follow the sun along a single axis and focus the radiation on a line focus. The intense radiation along the focal line is absorbed by a selective optical coating on the outside surface of a cylindrical metal heat transfer pipe placed inside an evacuated transparent pipe. The heat is removed by a heat transfer fluid to a storage unit or to a heat exchanger connected with a power conversion unit. In some system concepts, a heat pipe serves as a heat transfer device from the line focus of the concentrator to a local heat exchanger and storage unit. For a large power plant, the heat energy must be transported relatively long distances by means of hot fluid passing through pipe to a central storage unit, or to a power conversion unit. There are of course extra problems with heat losses during the heat transport process. Temperatures in the range of 300 to 600 degrees F may be obtained at total energy collection efficiencies of about 50% of the intercepted radiation.

In a second approach, a field of two-axis steered mirrors follow the sun and deflect the sun's image to a fixed absorber boiler unit mounted on top of a high tower. Thousands of mirrors can be deployed to concentrate direct sun light on the absorber boiler unit. The high temperature heat absorbed at the boiler surface can be used to produce steam or other vapors to operate a turbo-electric generator. Temperatures greater than 1000 degrees F. can be obtained at relatively high total collection efficiency.

Still another approach to solar thermal power conversion is an adaptation of flat plate collectors to higher thermal temperature collection. Temperatures in the range of 300 degrees F. may be realizable at acceptable collector efficiencies. The advantage of flat plate collectors over the radiation concentrating techniques is that such a system can use diffuse as well as direct sunlight.

The technical feasibility of solar thermal power systems has been established by a number of experimental facilities. As long ago as 1913, in Egypt, an array of cylindrical collectors totalling about 13,000 square feet was used to concentrate solar energy to produce steam for operation of an engine to pump up water. This power system produced peak power of more than 50 horse power. It operated for several years.

More recently, several solar furnaces have been constructed in which mirrors with two-axis tracking are used to concentrate radiation at a central point for high temperature experiments on materials. The largest of these is located at Odeillo, France in the mountains near its border with Spain. This solar furnace generates one megawatt of thermal power within a two foot diameter to create temperatures of the order of 7,000 degrees F. This heat could be captured in an absorber boiler, used to generate a hot gas, and converted to electricity in a turbine generator.

At the present time the Federal government is supporting ten outside projects with a total value of about $2.5 million dollars. Of these projects, nine are supported by NSF and one by NASA Lewis. There is some work being done in Federal laboratories operated by NASA and AEC. Major research problems remain in the areas of collection and concentration; heat transfer and storage, heat exchangers and boilers, materials performance, and component lifetimes. Special problems include high temperature selective optical coatings, reflector designs and optical coatings, thermal insulation, thermal transients, material fatigue, and material compatibilities.

Passing now to photovoltaic conversion, the general objective is to develop low-cost, long-life, reliable photovoltaic conversion systems to be commercially available for a variety of terrestrial applications. More specific objectives in the five-year plan are to reduce the cost of solar cell arrays made from single crystal silicon wafers by a factor of more than 10; to provide the research base for alternative solar cell technologies, i.e., CdS, GaAs, thin film poly-crystaline silicon showing low-cost potential; to conduct systems and applications studies for low-cost fabrication of cells and arrays; and, to identify a system proof-of-concept experiment projecting power costs a factor of 10 lower than present costs. The Federal funding for photovoltaic research and technology for terrestrial applications is estimated to be about three million dollars in FY74.

The use of semiconductor solar cells for direct conversion of solar radiation to electricity was first shown in 1954. To obtain a photovoltaic effect, combinations of transparent semiconductor materials or semiconductor and thin film metal materials are placed in intimate contact to form junctions. These junctions introduce internal fields that in the presence of light to produce electrons or ions give rise to a potential difference and an electrical current, if an external circuit is closed. As long as there is a source of light of appropriate wave length, the device is effectively a small battery or generator delivering direct current electrical power. Photovoltaic power systems are inherently very attractive because of the direct production of electricity, the absence of moving parts, the response to diffuse as well as direct sunlight, and the fact that a large heat rejection system may not be required.

The most highly developed and most understood photovoltaic device is a silicon single crystal solar cell that is used extensively in space power systems. These cells have been demonstrated to be highly reliable and useful in a wide variety of space power applications. They are equally reliable for producing electrical power on earth. Efficiencies greater than 10% in the conversion of solar energy to electrical energy can be obtained at high device yield with present technology. Efficiencies of 15 to 20% have been obtained for advanced cells.

Single crystal silicon cells are unfortunately very expensive to fabricate. About $30 per watt for moderate quantities of cells with at least 10% conversion efficiency to sunlight at the surface of the earth. For a large power system with these devices placed in arrays, power would now cost considerably more than $30,000 per kilowatt electric.

There are other photovoltaic materials to be considered as alternatives to the use of silicon. These include thin film heterojunction materials such as cadmium sulphide/copper sulphide, heterojunction materials such as gallium arsenide and aluminum arsenide, metal thin film junctions such as Schottke diodes, and others.

Silicon solar cell arrays are used extensively as space power supplies including a 20 kilowatt unit aboard NASA's skylab Space Station. Also, silicon solar cell arrays are used extensively on earth as relatively small remote power units for communications and warning lights. Also there are a few larger installations to pump water.

At the present time the federal government is supporting 15 outside projects in the photovoltaics area with a total value of about $1.8 million. Of these projects, 10 are supported by NSF and five by NASA laboratories. There is considerable additional work being done in laboratories operated by NASA and the AEC. Research and technology in photovoltaic conversion requires the highest technology. In particular, solid state and materials research technology will play an important role. Major research areas include new approaches to fabrication of single crystal silicon wafers and solar cells and fabrication and characterization of polycrystalline silicon cells and cadmium sulphide/copper sulphide cells; investigations of stabilities and effects in heterojunction and homojunction cells; investigation of crystal defects and impurities on device performance; and, characterization of new combinations of photovoltaic materials.

In the area of bio/mass production and conversion, the general objective is to prove the economic feasibility for large-scale conversion of organic waste, cultivated organic materials, and water to form gaseous, liquid, and solid fuels using bio/logical processes. More specifically, the five-year objectives are to provide an improved technological base for anaerobic conversion of organic materials to methane gas; to show the technical feasibility of producing hydrogen from water by photosynthesizing bio/logical organisms; to identify cultivated crops and associated technology and systems to produce fuel resources; and, to complete a system proof-of-concept experiment through the test and evaluation phase to study the production of methane gas from urban and organic wastes.

The federal funding of research in this area is estimated at one million dollars in FY'74. At the present time, there are nine projects with a total value of $1.2 million being sponsored by the federal government in outside laboratories. Of these projects, seven are sponsored by NSF, one by NASA, and one by the Department of Agriculture.

In the area of wind energy conversion, the general objective is to develop reliable, cost-competitive wind energy conversion systems capable of rapid commercial exploitation. Specific objectives in the five-year plan include increased performance and new options for components, subsystems, and systems up to about 10 Mwe electric systems, and completed system proof-of-concept experiments through testing and evaluation for 100 kilowatt electric systems and for other systems in the one-half to two Mwe power level.

Windmills have been in use for many decades to produce electrical power and for centuries to produce water. In fact the largest windmill electric power system in the world had a peak electric output of 1.2 Mwe and was operated in Vermont in the early 1940's in conjunction with a public utility network. Though the system operated successfully for a number of years, it was dismantled in the mid-1940's after a material defect in the rotor led to a structure failure that was not repaired.

At the present time, the federal government is supporting four outside projects with a total value of about $0.3 million dollars, all of which is provided by the NSF. The federal budget for research on wind energy conversion is estimated at one million dollars for FY'74.

The last area I will be discussing is ocean thermal conversion. This source of energy is adjacent to the coast of the United States and consists of thermal differences between the ocean surface and the ocean depths resulting from solar energy absorption on the surface of the tropical oceans and the vast nearby cold water at 1,000 meter depth which has flowed from the polar regions. The general objective of the research program is to establish system reliability and economic viability of large-scale power plants converting ocean thermal energy into electricity. Specific objectives in the five- year plan are to establish the design of components and subsystems and to obtain subsystem performance data; to conduct system studies and subsystem experiments; and, to identify a system proof-of-concept experiment projecting a reliable, practical system.

A 22 kilowatt electric plant was operated for about 11 days in 1929 as a first relatively successful demonstration. A temperature difference of about 35 degrees F. was used to drive a specialized design turbine. Due to the relatively small temperature differences of the thermal source, the practical engine efficiency is only a few percent, so that very large quantities of water must move through a system per unit of power produced. This factor results in systems requiring very large components to handle the large cold and warm water volumes. Fortunately, extremely large replenishable volumes of both warm and cold water are available. At the present time, the Federal government is supporting two outside projects with a total value of about 0.3 million provided by the NSF. The Federal budget for research in ocean thermal conversion is estimated at $0.7 million for FY'74.

Now, I'd like to conclude by saying that the U.S. solar energy plan is based on the following conclusions: technical feasibility has been shown for each application area; support of research and technology in each area --along with phased project planning; consideration of socio-economic, environmental, legal and other issues; and attention to implementation and utilization issues--can lead to reliable and economically viable systems; each application area can make a substantial contribution to domestically available U.S. energy resources; and, each area should be developed to practical systems at the earliest feasible time. Research is underway and more is being initiated in the six principal areas of investigation.

Research and technology are identifying new approaches to solar energy systems, and are focusing on new and improved materials, components, subsystems, and systems in each principal area. System proof-of-concept experiments in each of the application areas are being programmed at the earliest feasible time to show projected performance and economic viability. Innovative ideas and existing research results must be applied effectively by marshaling the potential contributions of interested professional persons across the broad disciplinary areas covered by solar energy applications. Additional research results must be obtained through directed efforts as the needs for such results are recognized.

It is the belief of many of us as scientists and engineers that some applications, namely, heating and cooling of buildings, wind energy conversion, and biomass production and conversion can have impact on the U.S. energy needs by the early 1980's. Other solar energy applications, namely, solar thermal, photovoltaics, and ocean thermal conversion can become viable economic systems later in the 1980's.

The federal government is moving ahead strongly to prove solar energy systems as practical, important, alternative sources for the nation's energy.

COOLING ASPECTS OF THE CURRENT G.E., TRW, AND WESTINGHOUSE NSF CONTRACTS

Raymond Fields

NSF

I would like to tell you what the mission of the Public Technology Projects Office is. We are program managers and it's our job to try and design and conduct proof of concept experiments (POCE's). Because of the high priority placed on solar energy and in particular on the heating and cooling of buildings, at the present time the Public Technology Projects Office is working on the heating and cooling of buildings only. Dr. Herwig has already given you a thumbnail sketch of the phased project planning that we do. In the heating and cooling of buildings we're presently in the phase zero feasibility study for solar energy applied to the heating and cooling of buildings. We have three contractors: G.E., TRW, and Westinghouse. Each of these companies is looking at the United States and dividing it into climatologic areas as necessary due to the weather and insolation of the various geographical regions, and they are looking at all building types and boiling them down to a manageable group of categories and then they are creating system concepts which will meet the thermal requirements of these buildings in the climatologic areas that they have already decided on. After they have created these system concepts they will then assess the economic viability of the system. For instance, one test of the economic viability might be that the fuel saved by using the solar energy system pays back the cost of the initial capital investment in the solar system in five years or ten years or in some fraction of the life of the solar system.

This project is far more than a technical project has already been indicated. We know it is technically feasible. The problems are getting it economic, and to get it socially accepted. The studies will address themselves to the problems of building codes, and what kinds of zoning problems will be encountered. The studies must consider the esthetics of the systems. The proof of concept experiment must address itself to the needs of the building community, the designers of systems, the consulting firms, and the architects. We need to produce data so that the various companies in the United States that are interested in this field can assess the subsystems or the areas of the solar energy business that they will wish to enter. And of course, we have to look at the social impact that creation of a new business means in a way of new skills, dislocations of present skills and so forth.

In the economic assessment, the studies are looking at the total requirements of the building, the heating, the cooling and the hot water needs, trying to reach the point at which you have the best economic return. At this point all of the companies are assessing the various types of cooling systems, the heat pumps, the desiccant systems, the Rankine, and absorption, all with respect to utilization within a total building system. We're four months into an eight month study. The three companies have completed the data gathering and are now in the process of assessing the feasibility of solar cooling of buildings at the present state of the art.

One other output of this phase zero study will be to identify the improvements in systems or subsystems required in order to bring more types of applications into economic viability. We will begin projects to improve performance, as required, to increase applications.

We expect to start with the operation of the Colorado State University Laboratory this year. Dr. Herwig has already talked about it so I will just touch on it to say that it is a critically important program in our proof of concept program. It will give us baseline system data. Later we will use this laboratory facility as a test facility for new subsystems. Once it is set up and calibrated, we can substitute new subsystems to get a quick performance test.

We have also a Transportable Solar Lab. This laboratory will have two refrigeration systems. It will have the Arkla three ton absorption system and it will also have a Rankine cycle system driving a Freon compressor. When refrigeration is not needed, the Rankine cycle engine can be clutched to a generator. I think this lab will provide a great deal of data which will be useful to industry and will support the proof of concept experiments. This laboratory will gather insolation data and weather data coincident with the systems operations.

This past month we initiated work at four schools. G.E. is supplying a system which goes on the roof of a school in Boston. The system will be utilized to supply heat to the fresh air intake thereby reducing the heating load requirement on the school's heating system. The Honeywell system in a school in Minneapolis can be operated in three modes. This school requires heat year round. In one of the modes it will provide space heat to the school; in one mode, it will be used to supply hot water, and in the third mode it will supply heat to the swimming pool. The solar heating system at Warrenton, Va. by Intertechnology Corporation is going to supply all of the heat to five portable classrooms. It features a single collector with two large storage tanks buried in the ground. Based on present data it would appear that we can meet the entire needs of those five classrooms. The AAI Corporation is building a system which will go on an elementary school in Timonium, Maryland. This is an "E" shaped school with the collectors on the middle of the "E". The system will supply the entire heat requirement for that particular wing of the school. This system will contain a 15000 gallon storage tank. All of these systems will be in operation still this heating season. During this coming summer, we will operate these systems to determine the capability of each system to drive air conditioning equipment. The heat collected will be dumped. So while we will not obtain refrigeration, we do expect to gather useful data for later application to refrigeration.

Returning to the Feasibility studies, the contracts are due to be completed at the end of May. We're planning to hold a conference in Washington sometime in July at which time the three contractor's will present their results to all of you.

UTILIZATION PLANS IN THE RESEARCH APPLIED TO NATIONAL NEEDS (RANN) OFFICE OF THE NSF

Thomas H. Pretorius

RANN Directorate, NSF

I have been asked to talk about utilization plans, and I have accepted. I'll start off by saying that the A in RANN stands for applications, and applications means that we must find some way to plot a course of action from the research phase to the actual use. The RANN management calls this the utilization plan. In our RANN guidelines that we're publishing for all proposals that come to RANN, we're asking that three parts be included in the proposal. One is a research plan, one is a management plan, and the third is a utilization plan. I think this emphasizes the fact that the RANN management is going to be insistent that people who have grants or contracts from RANN are going to recognize a course of action to go from research to use.

This actually is a new twist of things. Most of the people are familar with DOD and NASA. In these two organizations, we have a very definite track record. We know almost exactly what it takes to go from research to use. We also have a situation in which DOD or NASA, and to a certain extent the AEC, control all of the elements in the cycle. Unfortunately, for us in RANN, we do not control all of these elements. We therefore, must recognize the motivating factors that are going to help move the programs through the cycle.

Harold Horowitz asked me to make one other comment to you and that is, that in all of our unsolicited proposals, we are insisting that these guidelines be followed. In the RFP solicitations which we recently put out and which a number of you have responded to, Harold Horowitz, the program manager, had already prepared the utilization plans and as such your proposals did not require one. Now, I'm sure that as this program begins to formulate and as you start down the road, you're going to get a little more questioning and a little more emphasis to make sure that you're following what Harold Horowitz has already implemented or suggested for implementation.

I think I'm going to spend just a few minutes telling you what we consider a utilization plan should include.

The first thing that I think you ought to have in your plan is an identification (and some kind of an understanding) of the need.

The second thing is that you should have recognition of your competition. You should have some ideas of what kind of programs you're competing with.

The third is the identification of your users. Who is going actually to use what you are working on, and what kind of a cooperation and relationship have you established so that you know that what you develop will be picked up?

The fourth item is that we feel we don't want a complete market plan or business plan, but we think that you should have some kind of a basic appreciation of what the market potential is for what you're doing.

The fifth thing is the item that most people usually recognize in utilization and that is technology transfer and information dissemination. Now almost everybody addresses these two points. What we're trying to get you to do is to address them in a more positive manner instead of the passive manner of just writing a report and putting it on a shelf. We would like some of the more positive actions to be taken. We would like to have some of these actions scheduled, so that we have some kind of a milestone check point in which you and we know that you're shooting for some goals that you're going to attain.

The last item that we'd like to see in your utilization plan is a budget. We'd like to make sure that you've included sufficient funds so that you can accomplish these items that you need.

I think that in this meeting of ASHRAE and the NSF, we are developing some additional relationships that are positive, and I think that we at RANN certainly welcome any of the suggestions or any of the recommendations that you may have to help make our solar energy program more useful and more beneficial to the nation.

OVERVIEW OF THE ASHRAE FORUM ON THE USE OF SOLAR ENERGY AS A HEAT SOURCE FOR ABSORPTION MACHINES

David Sutton

ASHRAE and Honeywell Corp.

The ASHRAE forum was somewhat restricted in scope, with the central discussion aimed at absorption machines as a way of utilizing solar energy for refrigeration and air conditioning. This workshop is considerably broader in scope. The annual energy consumption for residential and commercial buildings is often presented as 25% of the energy consumed in the nation. If you add to that 25% the losses associated with the generation of the electrical energy consumed in residential and commercial buildings, a more realistic figure is closer to 34%. I'd like first to comment on how this 34% breaks down. 11% is for heating of residences; 6.9% is for the heating of commercial buildings; 2.9% is for domestic hot water in residences, and 1.1% is for hot water in commercial buildings. Air conditioning in residences accounts for 7/10 of 1%, and air conditioning in commercial buildings consumes about 1.8%. While air conditioning energy might sound low, the growth rates is pacing all other areas of energy usage. The residential air conditioning growth rate is 15.6% per year and the commercial growth rate 8.6% per year. So you can see that the subject that we're addressing in this workshop is a rapidly growing problem that requires increasing attention.

In the ASHRAE forum we first discussed solar collectors and collector performance. We then covered absorption refrigeration machines and what performance they are capable of, finally we tried to combine the two to discuss system capabilities.

On collector performance there was some diversity of opinion. We discussed 200 degree F temperature levels as being realistically achievable with flat plate collectors. Using concentrating collectors it might be possible to attain temperatures approaching 1,000 degrees, but the economics do not seem favorable. We discussed the efficiency levels of flat plate collectors. The top number presented was 90%. When that number came out, there were quite a few people who challenged it from the floor. The lowest efficiency mentioned was 30% and I came away with the feeling that 50% was a realistic efficiency level for flat plate solar collectors.

We then proceeded to discussion of absorption refrigeration. The aqua-ammonia system is most commonly used today in conventional absorption refrigeration systems. The lithium bromide system in the subject of considerable current interest since it is capable of operating at lower source temperature levels, and is one of the top contenders being considered for use with solar collectors. It was apparent from the discussion that there are no cooling concepts available that are specifically designed for matching the capabilities of solar collection systems. The absorption approaches used to date, have taken existing concepts and modified them for best fit. The degree of improvement that could be achieved by designing an absorption system for optimum match with solar collectors is not yet determined.

There was considerable concern expressed over economics. There was also concern expressed as to the required heat transfer area when operating from low temperature sources. The acceptability of water cooling for the condensers of absorption refrigeration machines was discussed. Water cooling for residential systems was rejected by the air conditioning industry quite a few years ago because of the concern over water shortages. This then raises the acceptability of cooling towers for residences, apartments and for commercial buildings.

In the latter stages of our discussion there was an expression of concern as to the attitude of conservatism and pessimism that was being expressed. There were remarks to the effect that industry had to be more optimistic, and start to do some blue sky thinking. It was suggested that we should start moving ahead with absorption refrigeration using a water cooled concept. If we did that, it might set the stage for development work on air cooled systems.

Going on from there then we got into some discussion of the different kinds of applications. There was also discussion of the work to be done on the integration of the solar equipment design with the building design. There are several programs that are analyzing that question, and also the question of how to market solar systems, if feasible.

At that point we got into the question of investments and payoff. Using the investment appraisal criteria normally used by the heating and air conditioning industry, solar heating and air conditioning makes no sense. This being the case, the role of government is very important to stimulate industry to apply its technical capabilities to some of these challenging problems and to provide the motivation to go ahead. We are pleased to see the important role that the NSF and NASA are playing in this area.

Harold Horowitz talked about the request for proposal that went out last fall for work in the various areas of solar energy utilization and solar cooling. I believe he indicated that the response from the industry was excellent and that industry was actively working the problem and was responsive to the idea of working with government to get the job done.

In conclusion, there has been some suggestion that maybe solar cooling was so tough that we should be moving ahead with heating and domestic hot water and let the cooling phase in later. It has also been said that these things are all technically feasible and it's just a matter of working out the economics. That might well be true, but the question of solar cooling technical feasibility and the best approach is still very fuzzy. This is the key technical challenge, and is the challenge to this workshop group. You have got a big problem under the microscope and I think it was wise to schedule this session in Los Angeles at this time, since it is important that we get people from the industry and the membership of ASHRAE looking at the problem.

Opening Session Overview Presentations

Commentator: Lloyd Herwig

NSF

Questions and Answers:

John Carr, Boeing Company: When will the results of the phase zero studies by GE Westinghouse and TRW be available in documented form?

Raymond Fields, NSF: Well I assume about the same time, about the end of June.

Anonymous Questioner: What temperatures are needed for absorption systems?

David Sutton, Honeywell: Thank you for bringing it up, I think that it is an important point. I think that the people that are working in the area of solar collectors feel that we're very close and can make the technical advances there to be realizing temperatures in the area of 200 to 230 degrees perhaps. This is harder at the north pole than it is down here in Los Angeles but that point did come up yesterday and I think that there was a feeling that perhaps we should be proceeding with work in the area of absorption machine development that assumes that we are going to be successful in achieving those temperature levels. I am really not too knowledgeable in that area and John, I don't know if you would like to add to that, perhaps you could give the group a little better perspective than I can.

John Yellott, Arizona State Univ.: I really can only speak with any certainty about the lithium bromide systems, where the operating temperatures are in the range of the low 200's. 240F is an optimum temperature for the machines in commercial use today, but they can operate at 200 to 210 degrees. There, the machines aren't quite as efficient as they are at higher temperatures. We are talking about current day machines designed with the most economic heat transfer surfaces. We can of course design machines with larger heat exchangers and thus lower these temperatures, but it's a tradeoff on economic cost. How much surface should be put in to lower the operating temperatures? With respect to limitations, we are also dealing with a heat sink in the form of a cooling tower for these water-cooled machines, and we can't use such low heat source temperatures that they approach the temperature of the heat sink. We must have some substantial temperature difference for rejection of the heat from the absorption machine to the cooling tower.

George Löf, Colorado State Univ.: I have a suggestion as to why there was such a broad range of efficiencies mentioned in the conference that Dave Sutton spoke about and a suggestion as to how all of those numbers can be reconciled. I believe he used the range of 30% to 90% and they can all be right. The reason being is that efficiency is a function of two very important variables. The amount of solar radiation and the temperature of operation above ambient. So I would like to suggest when efficiencies are talked about for a solar collector, it should include a mention of these two factors. For want of anything better, it's convenient to talk about efficiency at a condition at which the heat delivery from the collector is about 100 degrees F. above ambient temperature so if your ambient is 40, you're delivering at 140, if it's 90, you're delivering at 190 and so on and with a solar radiation level, that's specified and the convenient one there is about 300 BTU per square foot per hour. I think under those conditions, you have now the kind of environment in which an efficiency really means something, and a good collector under those specified conditions should give you somewhere around 50% efficiency.

Lloyd Herwig, NSF: I think I should say something about this issue which has come up both this afternoon and at the forum on Tuesday morning. There is a problem that has been recognized in which people doing work with solar collectors report their data on what seems to be different basis. This, of course can be confusing. We're trying to work ourselves out of that situation. At the present time, NSF has an award for a study at the National Bureau of Standards which hopefully will give us by June some tentative testing procedure for solar collectors and also for energy storage devices for use with solar systems. We would like to make that available to the people who are doing research with collectors and energy systems both as a way of the proposed testing procedure and as a way of trying to have the data which comes out of these programs be in more consistent and comparable form than it is at the present time. The two co-principal investigators for that project are Dr. Jim Hill and Dr. Tamami Kusuda. I know that Dr. Kusuda was at the ASHRAE meeting, and several times was on the verge of jumping up and addressing this issue, but he never quite made it. In any case they are at work on this project, and hopefully by June we will have a piece of paper from them which will be their recommended tentative testing procedure. It will offer their proposition on how solar collectors should be tested and rated and how solar energy storage devices should be tested and rated.

Walter Sargent, University of Maryland: I would like to ask the representatives from NSF if you can give us some idea of how in the future you plan to award grants for studies in solar energy. Will it mainly be by the program solicitation and RFP route, or will there still be room for unsolicited proposals?

ANSWER: Yes.

Pete Collin, Mechanical Technology: I would like to echo that earlier comment about high temperatures when it comes to dynamic machinery for cooling or for generation of power. It's very well known that the higher the inlet temperature of the machinery, the more efficient we can make it. I don't see in the program anywhere here any specific discussion that would give us machinery types a better feeling for what temperatures we can expect in the future from either flat plate collectors, or concentrating type collectors. I think that to me and my type of people this is very important input and I don't see much coming out yet from this meeting. Will it come out?

Harold Horowitz, NSF: It probably won't. That's a legitimate question. You're complaining about the weakness of having a specialized workshop. We left the collectors, storage devices, and other components of the system out of this workshop to concentrate on cooling components. The one previous workshop that we've had on heating and cooling of buildings in March of last year covered the waterfront. Now we feel that there's enough work going on in the component areas so that in order to treat them properly, we have to concentrate the subject matter in the time. Thus we weren't planning to lay before this audience some of the interesting work that's going on with collector development that may give us some higher temperatures maybe, and certainly lower costs and other kinds of improvements in a few years. I'm afraid you may have to come to some of the next workshops to get that kind of data. We are concerned about giving you more information in those areas in the near future. We have some plans about having a next workshop meeting later this year where we will try to cover the collector subject and the energy storage subject.

The proceedings of the heating and cooling workshop are now available. This is the workshop that was held in March of last year. It was held in Washington, it was organized for us by the University of Maryland, and the final proceedings is available from NTIS (Allen, 1974) and it covers the whole range of subject matter. We hope very soon to make the contents obsolete.

Elmer Streed, Lockheed Research Laboratory: I want to ask Ray Fields. Is the geographical route and the time schedule for the Honeywell Vans known at this time?

Raymond Fields, NSF: No. the exact test schedule is still being worked out. The van is built now and is still in the shop. Outdoor tests at the Honeywell Research Center will begin in the next week to ten days. When the system is delivered initially it will have heating, space heating and hot water only. At the end of April, after a field test at the NBS, at Warrenton and at Timonium, we return it to Honeywell where the two refrigeration systems will be installed. The real field test program will begin in June.

Anonymous Question: Is it possible that the van might come by the vicinity of particular researchers, so that they could compare performance data with their measurement equipment and with their own test models and this sort of thing?

Fields, NSF: Well we'd be happy to discuss that with you. We haven't put the test schedule to bed yet.

Anonymous Question: Is there a plan on flat plate collector optimization that you can project to some point when you think you would want to stop and then say go with your subsystem integration? Is there going to be a future solicitation similar to the solicitation November 28 A1 category, or do you see a point where you'll say, "Hey, I think we're close?"

Horowitz, NSF: Well, that's an awful hard question to answer. We have no plans to do a solicitation like the one we did this past year again. The circumstances were very unique, in that we were trying to address many problems and more problems than just advancing to technology. We were trying also to build up the number of workers in the field. Prior to this current year there were very limited number of on-going solar energy research projects in the United States and very few people involved. We were all hearing the same names of people working in the field over and over again. We were really very much interested in knowing who was out there that had ideas. The program solicitation that we had this past year, was an attempt to find out what kinds of ideas were out there and now we know. There are a lot of good ideas and a lot of capability. I think in the next year or so, the whole program is going to move on to another level of sophistication. It's extremely difficult to predict at this time what a terminal point will be. We would like to think in terms of a terminal point three to five years from now, and that's what we're talking about.

Raymond Fields, NSF: May I add a little to that? If our proof of concept experiment program goes as we expect, we'll start off with a certain area of applications that is viable now and we'll do what we call a critical subsystem research program, while phase one. the preliminary design, is going on. There may be indications of very specific system improvements that are needed to increase the impact of utilization of solar energy.

Lloyd Herwig, NSF: Well you now have slightly less than two hours before the start of the evening session that is going to be conducted by Sidney Sternberg dealing with the problems of the technology implementation. We don't want to wait three to five years when we have this great technology before we start worrying about how we put it to use. We'd like to begin discussing and considering some of these issues now so I'd like to call this session to an end.

SESSION I - TECHNOLOGY IMPLEMENTATION

Session Chairman: Sidney Sternberg

INTRODUCTORY STATEMENT

Richard Schoen

UCLA

In format and content, this panel session differs somewhat from the others in this workshop. It is primaril_ non-technical in nature and yet its content has a great deal to do with the ability of solar technology for the cooling of buildings to eventually achieve widespread commercial utilization.

Relative to other solar technologies for buildings, solar cooling is perhaps furthest from being a commercial technology. Unlike solar water heating, for example, solar cooling for buildings requires even now considerable basic research and development in order to demonstrate technical feasibility and economic viability. However, experience has shown that achieving both these objectives does not in turn guarantee acceptance and widespread use within the building industry. Not infrequently, a technology which has demonstrated satisfactory laboratory performance subsequently fails to impact the commercial market-place significantly because it has failed to fit the functional and institutional mechanisms which characterize the industry for which it is intended. Achieving industry-fit in housing and construction requires understanding and dealing with these issues in terms of: roles and attitudes of individual participants; shared industry attitudes towards innovative technology; testing and approval processes for building codes and the frequent vagaries of the codes themselves; skilled building-trades unions' attitudes and jurisdiction agreements; overriding first-cost concerns in certain building - type markets; construction financing procedures; etc.

The relatively early position of solar cooling technology on the normal production development scale which stretches from basic R&D through various steps to commercial availibility, provides the development process for this technology with a unique opportunity. Immediately following laboratory proof-of-concept experiments, e.g., showing that the technology works, further development of the technology can involve non-technical experts capable of addressing these primarily institutional issues. If both technical and non-technical researchers manage to work in an integrated and iterative fashion, the various product-lines which result at the completion of the development cycle will by definition have greater probability of commercial viability.

There are, in fact identifiable processes of implementation and commercial diffusion of innovative technology within the housing/construction industry.

A first step toward such integrated approaches to technological development is that the institutional characteristics of the industry be understood by all involved in the process. While studies have been recently carried out on the problems of institutional barriers (ref. Schoen/Weingart/Hirshberg 1974 Ford EPP Study) and conferences have been held on this topic (ref. the coming MITRE Corp. conference on the subject), it was felt that first-hand interaction between key industry participants whose roles will impact industry feasibility for solar technology, and the solar research community could more graphically depict the realities of these issues than could mere paper studies.

In order to achieve this kind of communication, a combination of selected industry participants and solar researchers were selected for this panel discussion. In turn, a focus for the discussion was created by developing a series of questions relating to these issues. An attempt was then made to match those questions to responders on the panel, in terms of each one's particular expertise. A summary list of those questions follows below. Each question is then repeated as a heading for individual panel member response.

The list of questions provided to each panel member was headed by the following statement, labeled "Context":

> "The distance between the essentially engineering research prototypes now existing in solar technology and the advent of commercial off-the-shelf systems is as risky as it is exciting. The purpose of this panel is to ask at least some of the questions which will have to be answered along the way."

1. What is the framework for the total cost of bringing solar air-conditioning to the market and the percentage of costs and risks associated with each function, including: engineering development; plant, capital equipment, and training associated with manufacturing, marketing, and distribution; and financing?
   a. Who are the customers and what might be the potential total market for the manufacture, distribution, sales and installation of solar air conditioning?
2. What information on performance, delivery, and product guarantee does the designer/specifier need in order to freely utilize solar air conditioning?
3. What part does the final user of solar air conditioning play in product acceptance and market demand?
4. What characterizes a useful demonstration project that will effectively encourage industrial participation and market penetration?
   a. What methods might be effectively employed to create and make a viable market for solar air conditioning?
5. What role would ASHRAE perform in the commercial implementation of solar air conditioning?
6. What are the specific technical needs for the earliest commercialization of solar air conditioning?
7. What efforts are required in the diffusion of technical information on government-sponsored research in order to encourage the development of solar air conditioning to its full potential as rapidly as possible?
8. Are there changes required in existing building codes, evaluation, and approval processes that would be required in order to install solar air conditioning in buildings? If so, please identify.

9. What role can major urban communities plan in the implementation and diffusion of solar technology for buildings?

Following individual responses to these questions by the various panel participants, a "wrap-up" and discussion of related issues was presented. The session closed with a question-and-answer period opened to the floor.

QUESTION: What is the frame work for the total cost for bringing solar air conditioning to the market and the percentage of cost and risk associated with each function including engineering development, plant, capital equipment, and training associated with the manufacturing, marketing, distribution and financing? A. Who are the customers and what might be the potential total market for the manufacture, distribution, sales, and installation of solar energy?

Response by

Alwin B. Newton

York

The question is more complex today than it would have been 20 or 30 years ago when I first started in this business. I think nothing is now attempted, by the larger companies at least, unless they have an assurance among all departments of the company that whatever product is being considered can be defined accurately as to: what it is supposed to do, how it will be used, what size market it will have, whether it is a growing market, who is that market, is it a market that that organization can reach, and can they sell to that market? All these things have to be addressed and looked at pretty carefully. The company would also have to look at the route to market. It might be quite different in a brand new situation than it is in serving the air conditioning, refrigeration and the heating business, for example.

Another thing that makes it different today, is the degree to which a manufacturer feels greater responsibility for the product. The days are gone when one used to say, "Well, here is a new product, let us make 50 or 100 of them and see how it goes." Usually you can not afford this any more. The cost of design, the cost of satisfying yourself all along the line is much greater than it used to be. So if you are now selling 40,000 units of some air conditioner for example, I believe you would be looking down the road to why you want to sell 40,000 units of something that replaced it. So you have got to have more complete design, more certainty that it is going to do what it should do.

To answer the first part of this question, I believe any company would first analyze all these little factors under a project. Someone would be assigned to it, and I can not imagine that it would cost less than say, $150,000 to $250,000 to really analyze it and look at it among the different departments in an organization. So you want to be pretty sure of yourself when you start in and all the work that is going on now under NSF projects prior to phases three and four is for the purpose of helping manufacturers be more sure when they do attempt the actual release of the product.

After one has decided that, yes, it is something that justifies development then you go through a design and release period. I will just simplify it to that extent. I do not know how many steps some of us have. I have seen organizations that have 50, 55, 60 steps in the design and release of the product and a few others that were down to 15 or 20. But they are all going to try to accomplish the same things. In doing this I would be surprised if the range of expenditures, assuming now that you are going to get in to a volume market, will not run $750,000 to five or six million dollars. So again, there is a large commitment on the part of industry to get into a new field.

Now in doing this, there are a few things that help us and I presume we may get a little further touch on this later in the panel, but I do not know how we would start such a project without having standards so that we could buy components like collectors for example, and know that we bought them on a comparable basis no matter whom we bought them from. We have got to be able to tell what the performance is. We have got to know something about the codes, and how we can live with those codes in anything we can do.

Such things as accessory power analysis has to be done in the solar field just as it does in all our other air conditioning work. It was startling to some of the people years back to find out that on water cooled systems, it took as much power for some water company to pump the water to the system and through it as one would add if one changed to an air cooled unit. And in solar systems we are going to face that kind of question, how much other power are we affecting?

Then assuming that one has that product design, then one still has to make a decision, "Do we make it?" I guess every organization has ways of determining whether or not to make it. Some people may be courageous enough to say, "we are going to plunge into this, we are going to tool up for it, and we will try it out right away and develop whatever it takes to sell it." Others may wish to go into a pilot shop operation in making a number of units. These are not production units, just pilot units. That causes a delay but it does increase safety and you do learn some things that you would like to change before you are in production. So it would cost another million dollars or so to go through a pilot program.

Then one comes to tooling, and the building of the factory if necessary. The amounts there will vary. But I can give you one example of our own, one situation that I was involved with. We spent about six or eight million dollars in a field that looked good to us and then we came to the point of production at which it would have cost 25 to $30,000,000 to tool a factory in a way that it could be competitive. The product is still not on the market ten years later. The actual competitive situation did not justify spending that kind of money.

I can not give you a figure for the kind of product that we are talking about but it is likely to be a figure at that level. Somewhere pretty well up if you are going to make lots of units such as this. You must not only tool up the factory, but you must tool up the sales department and the training department. And this again, must be looked at and the cost may be a nominal $500,000 or so.

Adding all the suggested costs together shows probable total costs to reach a reasonably high level of production in any one organization for new items such as Solar Cooling as follows:

Project Analysis	$150,000	to	$250,000
Design & Release	750,000		5,000,000
Pilot Program (optional)			1,000,000
Tooling & Factory	25,000,000		30,000,000
"Tooling" Sales	300,000		500,000
TOTAL	$26,200,000		$36,750,000

It should be noted that there are many organizations looking for the right place to invest such sums.

I think the reason for having this particular question on the agenda is to emphasize the fact that after the preliminary work (such as our present projects) is done, a lot more expense has to be anticipated and covered by industry to get a product on the market. I think it is very important that as soon as there is enough encouragement in any given area, that somebody begins to look at a parallel program to determine some of these other factors early enough so that we do not delay another year or more where we might have saved time by some overlap.

QUESTION: Who are the customers and what might be the potential total market for the manufacturers, distribution, sales and installation of solar energy?

Response by

William S. Fleming
Syracuse University

The total market potential of solar energy is basically concerned with solar energy's market profile and the variables of that profile. Solar heating and cooling variables, into which the market profile must be divided are: the marketing system, the market segments, the market potential and the resultant needed market penetration.

The Marketing System

Solar energy's marketing system must be further subdivided into a solar syste s technological variables. The entire solar system may be produced by one manufacturer as a packaged industrial product. As a packaged product a typical market channel could consist of the wholesaler, retailer, or direct to the final consumer. Another potential marketing system could be various manufacturers producing portions of an entire solar system. The marketing system would supply solar system components to one particular manufacturer and to the industrial market. Another potential marketing system would be various manufacturers supplying portions of the solar system to utilities. Utilities would then market the entire solar system as an energy producing product to the consumer.

The variable in the marketing system that must be considered first is the technological variable. The second consideration would be the technological and market development interaction and as Mr. Newton said that technical portion could amount to up to five million dollars. From past experiences large technical development cost can usually be multiplied by five to seven prior to producing a long term profit. A solar system is not in a near term profit category because of the vast amount of technological requirements.

The Market Segments

In my opinion the initial market will be public construction. The second market segment which will accept solar heating and cooling will be commercial and industrial and the third residential. The rates of acceptance and resultant time lags of the market segments will vary from five to ten years with residential not having a reasonable market share until 1985.

The Market Potential

The market potential will initially relate to the quality of a solar system just as quality relates to all HVAC systems. The second item is quantity which will have a direct relationship to the capital costs of the solar system. The third market potential item is the marketing source and the technological background. If XYZ company attempts to market a solar system such an attempt may fail mainly because of the company's current products, consumer acceptibility and share within the industry. The fourth market potential item is innovation and the market's acceptance or resistance. On many occasions resistance to an innovation occurs and due to esthetics, past experience, codes, and maintenance of the collector, consumer resistance to solar energy innovation may evolve. The fifth market potential item is price and as previously discussed quality and quantity have an inner relationship. The marketing of high capital/ low operating cost systems will be discussed in an example of a marketing system.

Market Penetration

Successful manufacturing and marketing of solar heating and cooling systems will require market penetration of current HVAC systems. The basic reason is that 99.99% of the current market is, at the present time, gas and electric. The market penetration will cause a resistance by utilities and manufacturers which is again a non acceptance of technological innovation. This non acceptance of innovation will be utilized by the utilities and manufactures who are not marketing solar heating and cooling systems to resist market penetration. Market penetration strategy must consider current HVAC systems which have competitive advantages and face the fact that these competitive advantages will be optimally utilized regardless of what we think of the energy crisis at this time.

Market penetration strategy must consider some HVAC manufacturer's concept of solar system nonfeasibility. Relative to this consideration, some are not involved at the present time although the NSF is providing resources for technological development.

An Example of a Marketing System

To provide solar heating and cooling with a marketing and technological example, I have selected the total energy system. When analyzing the market profile of total energy systems they were primarily initiated as a technological innovation. During the 1960's, the market rose substantially. As the 1970 era came upon our industry, the total energy market subsided. High capital cost caused the market strategy to be based upon the operating cost, and the capital/operating cost economic relationships. The strategy also included marketing by utilities who gave the system their utmost in marketing profile. The manufacturer and utilities marketing strategy included and produced the E-cube economical program. The market strategy of the total energy system could very well be utilized for solar heating and cooling; hopefully to a better conclusion.

The Market Potential

In my judgement, the potential solar heating and cooling market share will be one to three percent by 1980, two to five percent by 1985, and four to eight percent by 1990. The aforementioned market share projection is based on an assumption that there is optimum occurrence within the marketing system, segments, potential penetration and the need for new energy resources continues. There is a marketing model that relates directly to the potential market of solar heating and cooling which itemizes the interaction between technological and market research. If the aforementioned research results are placed into various plans which are based on quantitative analysis an optimum strategy will be developed.

Conclusion

There are differences in perception of the adaptation process by engineers and marketing individuals. My background and experience includes both engineering and marketing. If engineers and marketing professionals are working independently, the rate of acceptance of solar heating and cooling could possibly be impeded by both the marketing and the engineering profession. The acceptance rate of solar heating and cooling technology can only be accelerated by discovering causes of resistance within professions, the consumer acceptance relationships and faults within both the technical marketing system. Causes of resistance and faults must be put forth in an interaction mode between the engineering and marketing profession. The engineering profession commonly believes that technological development evokes market development. The marketing profession commonly believes that market development evokes technological development. Therefore, the interaction of both the technological and market development will accelerate solar heating and cooling acceptance at the lowest capital cost. These interaction characteristics will; reduce time, monetary lags and speed up both the product and market development. With interaction between the marketing and engineering profession the data collection and the planning activity will be increased and the likelihood of acceptance, penetration and greater market share will be increased.

QUESTION: What information on performance, delivery and product guarantee does the designer specifier need in order to freely utilize solar air conditioning systems?

Response by

Richard D. Miller
Feuer Corp.

In an effort to answer the question being posed, I'd like to give you my first hand feelings about utilizing solar energy in the design of air conditioning systems. Presently, the first step in designing an air conditioning system is to determine the peak heating and cooling loads of a building. Once this is established, equipment is selected with a known performance during a given design condition. That's the way it's been to date. The first thing that comes to my mind when one mentions solar panels is a piece of equipment that will have a varying output. Therefore, it appears that I must concern myself with match/mismatch variations of the heating and cooling demands of my building and solar panel rate performance.

Obviously, the design approach that I've taken to date will have to be altered. Now, equally important to the peak heating and cooling demand, will be the time rate heating and cooling fluctuations of building and equipment. How does my heating and cooling requirement vary over a given period of time, as compared to the performance of the solar collector during the same period of time? I become concerned about how I can readily establish time rate data for analysis. At the present you can easily calculate the conditions for heating and cooling using a slide rule. From that point, it is fairly routine for equipment selection. It now appears I'll have to resort to a computer, because of all the variables during a given period of time.

Once a computer readout was available, I would have a time rate output performance of a solar collector for the same timetable. I can readily foresee mass confusion if I were to have a computer readout with a timetable dissimilar to solar collector performance. Our industry functions on "cookbook" catalog data. For example, if I were to select a fan, I would have before me a chart in table form that would list for a given fan its CFM output against a given static pressure, the brake horse power required and the RPM. Performance data for a solar collector will have to be in a readily usable form to gain widespread acceptance in the industry. Quite frankly if I had to go through reams upon reams of paper before I was able to get the kind of information that I was seeking to proceed with design, I would have a strong inclination to consider solar energy and it's use an exercise of futility.

I've been told that solar collectors and the technology has been around for a long time, swimming pools and one story dwellings have utilized solar energy. Well, quite frankly, I'm relatively unimpressed. When one designs an 18 story building in excess of a hundred thousand square feet, we're talking about a completely different breed of animal than heating a swimming pool or heating and cooling a one story, three thousand or four thousand square foot building. It would be foolhardy for me to suggest a potential client fitting a building with solar panels with the present state of the technology. If my client were to ask to see solar energy at use and I took him out to a pool that's now maintaining temperature from a solar collector, or to a four thousand square foot house that is heating and cooling somewhere in Arizona, I would be minus one client in short order. What I'm really saying is before I would accept solar energy, I'd like to see meaningful performance, and when I say meaningful performance, I don't mean a simulated song and dance routine from a computer, but from an actual working model on a building of reasonable size where I have some reassurance that solar panels actually perform and deliver a reliable output of significant magnitude. In my opinion, this is a mandatory first step necessary to gain wide spread acceptance of what is still a new technology to the building industry.

Let's assume, I have accepted solar panels as a viable energy source, I'd ask such questions as: Who makes it? Is it competively priced? Will I be able to substitute a panel made by company A for a panel made by company B, if I need a replacement? How can I be sure that panels manufactured by different companies will have fairly equal performance? I think this is something that has to be looked into, and what I'm really suggesting is the need for standard industry ratings not dissimilar from the accepted ARI ratings presently available. I would then have some reassurance that I'm going to be getting a piece of equipment that will at least perform within a minimum requirement.

The next question that I would probably have is, how do I tie this solar collector or solar system into the conventionally heating and cooling systems that I presently know, and how do I control its use? What happens if I have 10 days of cloudy, rainy weather? Do I tell everybody to get around a pot belly stove until the sun comes out? Do I need to install a conventional boiler? What size should it be? This is a question that has to be answered. I would also ask what is the water pressure drop of solar panels and what would be it's impact on my pumping system. Equally important to all the technical questions that one can pose is the question of money, gentlemen, money! How much does it all cost?

Perhaps up to now, we've all concerned ourselves with presenting to a client a first cost comparison of the options available for heating and cooling. With the problem of limited fuels, and prices increasing constantly, I think one has to analyze a building not only on a first cost basis, but in terms of energy consumption costs for a given life. Depending upon the type of building in question if a solar panel system costs "X" number of dollars more than a conventional boiler plant, it might very well be the logical choice. However, let us not lose sight of the fact that we still are a first cost oriented industry. Questions, questions, questions as I talk about one question a whole array of new ones come to mind. What happens to performance if panel surfaces get muddy, clogged and dust falls upon it? What kind of maintenance would be involved for a solar collector? Will this system be acceptable to the local building department? Are the panels compatible with code requirements? My first response to solar panels is one of excitement tempered with caution. I will have to be convinced by a meaningful performance over a reasonable period of time before I consider solar panels as an acceptable option on the building I'm entrusted to design.

I started my little talk this evening by telling you that these are my first hand feelings about solar energy. I must now tell you that it was only moments before I was called to the podium that I found out the topic of my talk. My comments tonight in a very true sense are first hand.

QUESTION: What part does the final user of solar air conditioning play in product acceptance and market demand?

Response by

Jerome E. Scott

(University of Colorado)

Advances in the technology of solar energy utilization and the forecasted rise in conventional fuel prices suggest exciting possibilities for the future of solar energy. Technologies which appear feasible from a performance standpoint have been developed and are approaching economies of operation that might speed the diffusion of these innovations. But technological success does not imply commercial success. There are some very important problems that we should address in the area of consumer acceptance if solar heating and cooling are to be widely used in multi-family dwellings and single family units. Specifically, I believe we should consider: (1) areas of consumer resistance, (2) positive consumer motivations to purchase solar dwellings, (3) the nature of the demand curve for alternative concepts, (4) constraints limiting freedom of choice and (5) target market definition.

First of all considerable effort should be devoted to identifying the specific areas of consumer resistance to such a technology. Careful research with prospective buyers will be necessary to estimate the importance of various perceived problems, but let me speculate on some possibilities. Consider the problem of aesthetics. Clearly, if we proceed toward solar home development as has been shown with some solar water heaters, we will not get anywhere. There are issues of design, appearance, space requirements, solar collector type, placement and configuration which affect motivations to purchase. Certainly home owners buy their residences on the basis of aesthetic appeal, and I think it's important that we assess the relative appeal of different approaches. We may also expect reservations concerning maintenance, the fear of breakdowns, freezing, cleaning, storm damage, vandalism, inconvenience, lost time, and damage losses to the rest of the home. Questions will arise concerning the durability of systems: deterioration over time, periodic replacement cost, inconvenience.

There may also be more subtle, perhaps subconscious emotional or social cultural factors which could retard acceptance. Would consumers look at solar homes as living in a cold, antiseptic laboratory or a factory? Is there a threat to self esteem or self concept or other basic needs that individuals may have? Would, for example, a person who uses a solar home or a solar water heater be viewed as an individual who could not achieve an economic level sufficient to use a more desirable conventional system? Such an attitude would undoubtedly be fostered if solar units were to be placed on low income subsidized housing as a means of prototype evaluation. With this approach we would be asking the "trickle down" theory of diffusion to reverse its historic direction.

A second area is the identification of positive motivations to purchase. There may be powerful reasons why some people might prefer solar homes to conventional homes. The anticipation of increasing fuel costs and protection against power failures and fuel rationing should be of considerable appeal to consumers. Solar homes may also be promoted as a prestige item building on the rule of fashion which says, "I've conformed sooner than you have." When one sees an expensive car, one sees not just the physical chemistry of the product but also status, prestige, wealth, social position. Further, increasing social consciousness concerning the environment and ecology movement are producing more favorable dispositions toward products which enhance these values. I think it's vital that we identify what these positive motivations are and how they are distributed throughout society.

A third major area causally related to the motivations to purchase or not is the nature of the demand curve and associated elasticities for alternative solar home concepts. This information is vital in determining how price sensitive the market for solar homes appears to be as a guide to public policy. Moreover the analysis should try to impute monetary worth to non price variables as a guide to designers. We should assess the tradeoff between higher initial outlays and increased mortgage payments throughout the life of the mortgage.

A fourth major area has to do with possible constraints. There are many constraints which could serve to block the diffusion of solar homes: building codes, higher insurance rates, and in particular problems with financial organizations who provide mortgage money. Imagine a very frightening scenario, where the savings and loan industry refuses to permit the mortgaging of the incremental capital costs associated with a solar home. Imagine, if you will, a 50 thousand dollar home where the buyer is required to produce 20% down, and then an additional 6 or 8 thousand dollars of initial cash outlay to purchase a solar home. Such a condition would surely block the widespread use of solar technologies.

This suggests another area for investigation. Discussions should be conducted with authorities who influence lending institutions to obtain their viewpoints on various approaches. Included should be officers of the Savings and Loan Association of America, the Federal Home Loan Bank Board, and the Federal Housing Administration. If consumer demand analyses indicate that initial capital outlays must be kept down, then it may be necessary for the government to embark on some approach of subsidization. Such programs could take many forms. The government could guarantee that part of the mortgage corresponding to the solar home cost or tax reducing depreciation could be made available to home owners. Other suggestions have included low interest loans to builders or home owners as well as utility assumption of first costs.

A fifth major area is the definition of the market. I think it's very important initially that we locate where the market is and identify the initial consumer for solar homes. What are his beliefs, attitudes, values, and socioeconomic profile? What are his purchase motivations? How can such a person be reached and with what message? I think these are some of the important questions we should be asking ourselves now at this state in the development of solar heating and cooling. Morever, I think it is important that research be conducted now so that we don't try to go to market with systems that will fail to be accepted and therefore retard the ultimate growth of the industry.

QUESTION: What characterizes a useful proof-of-concept experiment or demonstration project that will in fact effectively encourage industrial participation and market penetration? What methods might be effectively employed to create and make a viable market for solar air conditioning?

Response by

Larry Papay

Southern California Edison Company

Southern California Edison is interested in "Marketing", or demonstration, as such, of energy systems-whether they be end use systems (as we refer t air conditioning, heating etc.), or front end systems (nuclear power, coal or what have you). Any viable demonstration project has three phases: The planning phase, the actual demonstration itself at a site or sites, and then what happens after the demonstration - the implementation program. I think it's important at the beginning, while carrying out the planning for a demonstration project, that participation or involvement of all interested parties be assured. This not only includes governmental agencies which may fund such projects, or the manufacturers of the equipment, but also the various trades that would be associated with the demonstration, the building designer, the architects, anc the utilities.

I might cite an example from the energy industry to underline this. Approximately ten years ago the Office of Coal Research thought it had a very good program going for the development of alternate uses of coal-synthetic fuels. However, to a certain extent they were carrying out this program in a vacuum and had not gone out and solicited the support and involvement of potential users, the coal or oil companies. Consequently, the program lagged and now with the shortage of oil and gas which might have been produced from these processes, it is too bad that there was not involvement of all interested parties at the beginning.

In the planning phase when the demonstration project is being designed, one must be sure to a) organize the data for the system design, that is, look at the usage patterns of the potential customers or sites, b) evaluate the air conditioning requirements for a representative set of commercial or residential buildings, c) do analyses to identify the allowable costs for subsystems, d) summarize the performance and cost characteristics of these systems and e) carry out economic tradeoffs and comparisons (combined heating and cooling, the cost for a new installation versus retrofit, and other things of this nature).

In the demonstration phase of the program, it is important that the first demonstrations be set up so that the economic data generated by the demonstration will be reasonable. If the demonstration program is designed poorly, it can create stigmas which will be borne by the industry for many years. This sometimes is apparent with hastily devised test programs. Several geographic areas should be included in the demonstration program to demonstrate that the economic operating characteristics of the devices to be tested apply over a variety of conditions. Also the demonstration should be conducted on a variety of buildings in the industrial sector and/or the commercial sector as well as a variety of private or residential structures. This will show that the demonstrations have been selected on an objective basis and that questions concerning the viability of the results will be minimized.

Now from a utility point of view, we feel rather strongly about being involved in the demonstration program because we have been involved with customers (if you like energy users) and their usage patterns. And we do have programs where we are involved with special needs of selected customers. Energy services and total energy systems were mentioned before, but there are other particular needs of customers, for backup service to name one.

Finally, as far as the test duration is concerned, I think we must allow for a considerable period of demonstration. As a bare minimum it would have to be a year so that one could get data for all the seasonal variations as far as the supply and demand of energy are concerned. Perhaps even longer than a year if the risk uncertainties are higher.

Now how do you implement once you've got the demonstration program underway or completed? Well implementation is dependent upon actions which are carried out at some prior time. You don't wait for the end of the demonstration and say, "Fine we've got a reasonable system, I think we can begin to go out and market it," because there are many factors which have to be considered. There are institutional or regulatory factors which will have to be resolved. For example, if there is a cloudy period and a supplemental energy source is required (whether it be electric or gas), how do you incorporate this requirement into a rate structure? Perhaps you go to a two element structure composed of a capacity charge for the customer plus a usage charge. In Southern California for solar heating there will be a high demand for supplemental energy when the solar heating system is least effective, that is, a cold cloudy day. Thus the demand for energy would be highest when the solar system is least capable of meeting that demand. Of course, storage is another aspect but there are still some needs.

If you were to get a utility involved in the marketing and application as was suggested previously, there is the fact that utilities are regulated industries. There would have to be work done initially in an educational process with the various regulatory commissions to set up the type of structures and allowances which would permit the utility industries to become involved in the ownership and/or leasing and/or maintenance of installed systems. The rate structure could be designed to encourage the installation of solar energy perhaps as suggested above. Southern California Edison is looking at the institutional factors to determine whether or not it would be feasible for a utility to be involved in a manner similar to the telephone company, that is, to own, lease or service equipment to the user. We do get involved to a certain extent in this way with some large users who require special services.

It is going to be costly to go through the demonstration phase. (I keep using the word demonstration in the plural because I think there will have to be a series of demonstrations of different technologies or different modular concepts, different manufacturers. There will have to be several of each type in different locations.) The federal government would probably participate in the cost of such demonstrations. I can't speak for all utilities but as far as our company is concerned, I think we would probably participate in such a program.

In closing let me point out that we were asked to respond to HR11027, Representative McCormack's Solar Heating and Cooling Demonstration Act. Our response was favorable, and I would like to quote from our response: "We believe utility involvement in the demonstration of solar systems is essential, because of the interaction and interface of that system with the utility system that is to reference true cost for the supplemental energy. Similarly commercialization may require services to the energy user similar to those now provided by utilities in connection with installation and maintenance of conventional systems." One final comment and that to second what a previous speaker had stated: that residential application, unless it's on a large scale apartment house, is probably lowest on the acceptability level as far as the user is concerned. The initial thrust should be made at the industrial or commercial level, or public buildings.

QUESTION: What role would ASHRAE perform in the commercial utilization of solar air conditioning?

Response by

John I. Yellott

ASHRAE and Arizona State University

About ten years ago, the ASHRAE Fenestration Committee (TC 4.5) proposed an entirely new method of calculating solar heat gains through architectural glass. The method was originated by Don Vild, then Chairman of TC 4.5, and when it appeared first in the 1963 Guide it was greeted with specticism. It reappeared in a revised form in the 1967 Handbook of Fundamentals with greatly improved tabulations of data, with more refined values of Shading Coefficients, and by that time it had been accepted by most of the engineers and architects in this country as a practical and accurate way of estimating solar heat gains through fenestration. By 1972, when the most recent edition of the Handbook of Fundamentals was published, the method had been so completely enshrined in the literature that it is now completely accepted in this country and also in France and England.

In the field of solar energy, the Technical Committee of Solar Energy Utilization (TC 6.7) is facing somewhat the same situation. ASHRAE is not a commercial organization, yet it is supported by commercial interests, because without the manufacturers, there would be no ASHRAE. I can see a number of things that ASHRAE can do without losing its non-commercial status. The first thing that ASHRAE has done and can do is to disseminate factual, practical, usable information on the subject of solar energy.

We have begun that by preparing a chapter on the current status of the art which will appear in the 1974 issue of the Handbook of Utilization, to be published by the end of July. Secondly, the major effort of the Committee on Solar Energy Utilization between the years 1964 and 1966 was the production of the monograph, now a best-seller and recently reprinted, called "Low Temperature Engineering Application of Solar Energy." It is interesting to note that there were eight members on the Committee which compiled that document, and three of us are on the panel here tonight. We are going to put out a new and greatly improved version under the editorship of Richard Jordan and Ben Liu. I trust that this will become as authoritative in the field of the solar energy technology as are the other ASHRAE publications on the design procedures for fenestration calculations.

At the Montreal meeting which will take place at the end of June, 1974, there will be a symposium on the present state of the art. By that time the National Science Foundation will have received many reports on the solar research now in progress and I hope that ASHRAE is going to have a part in the publishing of those documents. It is we of ASHRAE who are going to be faced with the responsibility of putting these proposals into actual use. It is going to be ASHRAE members who will sell them, ASHRAE members who will install them, and ASHRAE members who will make them work.

I am in favor of ASHRAE participating in the setting of standards for solar components, and this is one of the projects which TC 6.7 on Solar Energy Utilization has agreed to sponsor. We feel that, just as there are ARI ratings which mean a great deal to the purchasers of refrigerating and cooling equipment, so must ASHRAE set up standards which will be significant to those who are going to buy solar equipment.

Ten years ago, Austin Whillier, who was one of the contributors to the ASHRAE monograph on solar energy utilization, published a tentative standard method of testing solar collectors (Whillier, 1961). I have suggested to James Hill and his committee from the National Bureau of Standards that they review what Austin Whillier proposed at the Rome meeting back in 1961. We need a standard means of testing solar collectors so that when we begin testing them we can all do it in the same way and know that the results will be comparable.

One new thing which ASHRAE has undertaken (this again is a TC 6.7 activity) is the monitoring of research projects which NSF rather than ASHRAE is financing. We all know of the major work which ASHRAE has done with its own funds, but this year for the first time, we have been asked to participate in research programs financed by the National Science Foundation by supplying technically qualified monitors. They will help to evaluate proposals for future programs, and to help the sponsors of those programs look after the technical content and make sure that their quality is up to ASHRAE levels.

My own feeling is that the commercialization aspect of solar energy utilization will be expedited by having ASHRAE make sure by every means at its command that the quality of the products sold in the solar energy business will be high. There are many companies which are jumping into this field because they think there is a quick dollar to be made, and I can't think of anything more disastrous than for low quality material to be sold, for the customers to be disappointed and for the results to be poor. Then we would be right back where we were 18 years ago when solar energy first gained prominence very prematurely with a great hullabaloo.

The best thing that has happened to us is the shutting off of the cheap oil supply from the Middle East because when oil has gone up from $2.42/barrel to $24/barrel the economics of solar energy have changed quite radically.

May I ask a question before I sit down. What are the alternative sources of energy which the home builders of the future are going to have to look forward to?

QUESTION: What are the specific technical needs for the earliest commercialization of solar air conditioning?

Response by

Harry Tabor

The Scientific Research Foundation Jerusalem, Israel

All I can say is that there are a lot of technical problems ahead of us, but when I compare them with the problems that we have heard discussed just now on how you market solar energy and get it accepted I think the technical problems are trivial. In fact I must confess that I am waiting until tne end of this workshop in order to be convinced, and I know this is heresy, that there is a future for solar cooling at all. The reasons are not difficult to see. Probably the problems of technical acceptance and marketing and the fact that you have got to compete with much easier and more convenient systems.

There is no uniformity in the problem that faces us. Someone has mentioned that the acceptability will probably be first in public buildings and commercial buildings and then in residences. I think as far as the persons who are looking at the technical problems are concerned, these are completely different problems. To give just one example, it is a lot easier to build a 100 ton absorption machine than it is to build a 2 ton absorption machine. It is easier and the price is much lower, and the result is that I have no idea how you are ever going to build a small absorption machine which will work from solar energy. I mean it can be done on paper, but the question is whether you can get into the business of producing them and selling them.

When I mentioned earlier some hesitation about whether solar cooling in that sense was really feasible, I was thinking of the fact that maybe it would be easier to produce mechanical or electrical energy from the sun, and drive a conventional refrigerator unit. Though this also sounds like a kind of heresy, for the solar engineer it may be a more feasible proposition.

I will just mention a few technical numbers to get our thinking right. If you take, for example, a conventional cooling machine with a coefficient of performance of say four and you want four kilowatt hours of cooling you have to put one kilowatt hour in. If you take an absorption machine and you work very hard and you get a coefficient of performance of 0.6, and you operate it from a collector with an efficiency of about 40% (I wish I could say 50% but I can not with what we know today-not at the temperatures that people are talking about), that is an overall coefficient of performance of about a quarter. It means that you need 16 kilowatt hours of input heat from the sun to produce four kilowatt hours of cooling. If you had an electrical conversion system, of 6% efficiency, it would be easier to make electricity and drive a conventional compressor unit than it would be to go through an absorption cycle.

Now, I am not saying that 6% for an electrical generation system is easy either. And I am not even discussing the question of price because we know how expensive these systems are, but it does show very clearly that the coupling of the solar collectors to an absorption machine is at present an extremely difficult process. So that if you really want to work on absorption machines the technical problems are: can you make a solar collector that will operate at a relatively high temperature? And more important can you make it cheaply? Now this is a very serious question because it is fairly easy now you've got the ASHRAE book which tells you how to build a collector and how to determine its efficiency. If you want to put enough money into it, you can build a very good collector and get whatever temperatures you want at reasonable efficiencies. It just becomes very expensive. It has got a lot of materials in it: either glass or honeycomb or special surfaces or mirrors or something else. When you put it all together, it is a lot of money.

At the meeting sponsored January 21, 1974 by the Scientists Committee for Public Information (SCPI) at the U.N. in New York people were talking about having to produce collectors for $2.50/sq. ft. We know the price of materials is going up just as the price of fuel is going up, (ortunately not at the same rate). It becomes a terifying problem to see how you are going to make any sort of solar collector for $2.50/sq. ft. I think that probably after the workshop some numbers will come which will tell you very comfortingly that you can spend a lot more than $2.50/sq. ft. So the problem of getting the temperature up is one which people looking at solar collectors will have to think of. I am very worried here because the number of ideas that have been sketched on paper on how to build the solar collectors is so large, that it is quite hard to think that somebody is going to think of another one that has not already been sketched at some time. I do not close the door to a breakthrough here but I must confess that it looks very difficult.

Now as far as the absorption machine is concerned, there are of course basic thermodynamic limitations. Everybody knows that if you want to have a certain depression of the temperature, then the elevation that you need on the input side has got to be larger than the amount of depression you want. If you allow for the losses in the various heat exchangers it is probably between 1 1/2 times and twice as great so if you put in the numbers of what your condensing temperature is and what temperatures you want to get, then you will realize that you have to have input temperatures of around 200 degrees F. If somebody says well I will make you one that works at 150 degrees F, you will have to remind him that there was a man called Carnot, and he made a lot of trouble in this field.

One thing I can say is this, and it has cropped up in work at various times that has been done particularly on domestic refrigerators. In commercial absorption machines, the coefficient of performance is poor. And the reason is very simply that the manufacturer has skimped on the heat exchangers because he has to design to a price and he has ignored entirely the question of the cost of the energy. In fact, we have a rather tragic story in the early days of my own country where people decided to build domestic absorption refrigerators because they did not want the trouble of the maintenance of mechanical ones (mechanical ones are now very reliable, but at that time they were not). Also they thought that in the various parts of the country there would be no electricity so they made absorption machines that work with kerosene. Then since nobody wanted to work with kerosene they proceeded to heat them with electricity. The bills were so high that the electric company had to introduce a special rate to compensate the people, otherwise they couldn't operate the refrigerator at all. What I'm trying to stress is that I do not think one has to take the figures for coefficient of performance of absorption machines as they are today. If the manufacturer knew that there was a different method for calculating the cost and it would pay to put more money into the design of the machine and into the recouping of energy in the cycle, then the coefficient of performance could be improved and the operating temperature pulled down a little bit. I think that this is where there is room for technical advance.

The third place where I think technical advance is needed, (there may be some people who disagree here) is on the question of storage. It is true that cooling is unlike the solar heating problem, where you have a disagreement between the supply of energy and the requirement. In the case of the cooling, you tend to have more sunshine at the time you need it most. And so some people might argue that you do not need any energy storage. Personnally, I think that energy storage is absolutely vital. If you draw the picture of the peak solar energy and then consider the fact that the collector does not respond in the early hours, and in the late hours (because of the losses), the peak energy that you get out of any solar collector is limited to a rather small number of hours of the day. When the energy level is below the operating temperature, the thermal cycle will not work at all. It means in fact that you get a very peaky input to the system, and it means that all the heat exchangers in the cooling machine have to be several times as large as they would be if you had a storage system. We have, for example, a simple grapn describing the case obtained for a solar power unit to produce one horsepower continuously to compete with a one horsepower gasoline engine. You have to design it for something like 6 horsepower peak. That means everything is bigger and the efficiencies at the low values are poorer and all the parts are larger, and it is more expensive. Thus I believe that one of the things that has been glossed over and has to be considered most seriously, is the question of energy storage.

I would like to say that this is not a very easy nut to crack. It sounds easy and at the moment the best approach appears to be either water or a rock pile. Much work has been done on heats of fusion. A lot of tribulations have been suffered in this field and one of the discouraging facts is that some years ago a paper was written by Goldstein (1961) who was on my staff for a short time, who showed that on physical-chemical grounds, there wasn't much chance of finding a new material that was substantially better than existing materials. We have to be prepared for the fact that we are limited more or less to what we know today and the thing to do is to improve the packaging and try to find cheaper materials. But to get actually bigger numbers would be very difficult. So in summary I would say that the technical problems are the performance of the collector at a given price, the redesign of absorption machines if we decide to use the absorption system (of which I am not convinced at this stage) and improvements in storage facilities.

ADEQUACY OF PRESENT TECHNICAL PUBLICATION PRACTICES

George O.G. Löf

Colorado State University

John Yellott has presented a good picture, with which I fully agree, on the important role of ASHRAE in disseminating technical information on topics related to heating and cooling, including the embrionic data we have on solar energy use. I'd like to discuss two categories of information and the mechanisms for their distribution. One is strictly technical and the other is information in which the commercial practioner and the potential user would be interested. I may not have included all the channels and the media, but these are the ones that come to mind and I think are most important.

In the field of technical information dissemination, I think we are in a good situation. We have a number of media that I'd like to list. ASHRAE has a series of handbooks on fundamentals and on applications, and John Yellott has just written a section on solar energy to go into one of these. There is the very useful ASHRAE bulletin, "Low Temperature Application of Solar Energy" (Jordan, 1967), which I regard as a bible of practice insofar as we now know it. There are also the ASHRAE journals in which current technical information is published.

A second medium is the journal, Solar Energy, a quarterly published by the International Solar Energy Society.* This is an excellent publication for the dissemination of technical information on solar energy, and I commend it to you. For $20 a year you can become a member of the International Solar Energy Society (ISES) and you then receive this journal plus the announcements of meetings and the other prestige values in belonging to this prestigeous organization.

Thirdly, we have the solar energy division of the American Society of Mechanical Engineers, which has an annual meeting at which technical papers are presented. Suitable papers are then published in the various journals of the ASME. Finally, there are the technical reports that the National Science Foundation has available on the results of the research projects which they support.

Foreign publications are important even though we don't use those as media for our research results; they are useful to see what's going on in other countries. Heliotechnology ("Gelioteknika") is the Russian solar journal; the English translation is published by the Faraday Press in New York. This high quality journal is published six times a year. The Proceedings of the Mediterranean Solar Energy Society, known as COMPLES, are published once a year.

For the commercial practioner and the potential user, publications are very limited. The ASHRAE guides and handbooks are useful for the air conditioning engineer, and I think they'll become increasingly useful as the standardization of solar energy equipment, particularly solar cooling units, develops. Several newsletters are published. The ISES publishes a newsletter. There are several others - The Solar Energy Digest (SED) and High Country News, are representative. There are the architectural journals with occasional articles on solar heating and cooling. Films by commercial producers, newspapers, and popular books are also available. These media unfortunately do not have the objectivity that the technical literature does. It's natural

*Addresses of all organizations cited are listed at the end of this article.

for a newspaper reporter to write up what comes to his attention and his principal objective is usually something that is interesting. Technical reliability appears to be secondary to news value and the potential user may obtain false impressions. We need a better mechanism for getting sound information on new developments to the practioners and potential users.

Along this line, I would like to close with a suggestion. Perhaps the NSF should consider publication of a semi-technical journal, oriented specifically to the practioner, the architect, the heating and ventilating engineer, the contractor, and the developer, by extracting from the wealth of research and development results from the projects which it sponsors. There are some precedents for this. The Office of Saline Water (U.S. Dept. of the Interior) has published a journal known as Distillation Digest. It is a publication of this type, perhaps a little more technical than I'm thinking about in respect to solar energy. Reliable information, written from a very practical slant, could thus be provided to the practitioner. In the dissemination of technical information, we have adequate means, but we need to improve the supply of information to the commercial market.

Addresses of Organizations Mentioned

ASHRAE
345 E. 47th Street
New York, N.Y. 10017

ASME
345 E. 47th Street
New York, N.Y. 10017

COMPLES
Secretariat du COMPLES
Laboratoire d'Electricite et d'Heliotechnique
Faculte des Sciences, Annexe de St. Jerome
13 - Marseille 13 e
France

Applied Solar Energy (Gelioteknika)
The Faraday Press, Inc.
84 Fifth Avenue
New York, N.Y. 10011

Solar Energy Digest
P.O. Box 17776
San Diego, California 92117

National Science Foundation
Attention: Mr. George James, Information Specialist
Advanced Energy Research and Technology
1800 G. Street N.W.
Washington, D.C. 20550

International Solar Energy Society
U.S. Section Headquarters
c/o Dr. W. H. Klein
Smithsonian Radiation Biology Lab.
12441 Parklawn Dr.
Rockville, Md. 20852

Office of Saline Water
U.S. Dept. of the Interior
Washington, D.C.

QUESTION: Are there changes required and so identify, in existing codes, evaluation and approval processes that would be required to install solar cooling in buildings?

Response by

Edward Brownstein

City of Los Angeles

Generally our code deals with health and safety. What has health got to do with a solar heating system? What has safety got to do with the solar heating system? Our present codes probably cover these things in general but in particular they don't. A solar heating system is merely an energy source.

Now we could go into the particular codes. For instance there is a building code. Now the primary effect on the building code would be, what is the weight of a solar heating system? The building code demands that you design the structure to support it; there is no problem there. Next thing I have on my list is a boiler code. Ultimately of course we may get to steam solar systems. From the stand point of usefulness perhaps they'd be better, and if you get into steam pressure vessels we'd have to comply with the boiler code, but there is a boiler code existing and I don't see anything really special about a solar system. An interesting point about the Boiler Code in the city of Los Angeles as it is written now, is we take the state labor code which says that if you're in a place of employment, you've got to follow the Boiler Code. If you're in a single family dwelling, you can make things any way you please. The next thing we get into is the plumbing code. Within the jurisdiction of the plumbing code you might for a maximum efficiency take the pipes up on the roof, and let the sun bake the pipes, and run the water directly to your storage vessel. In this case the plumbing code would have a few requirements. It would say the wall thickness has to be such and such for copper tubing. Now probably you would want to use thin wall copper tubing and we would probably need a special approval on it, but I anticipate that the manufacturer could get one. Another thing is that you would need some kind of safety valve or energy cut off on your boiler because conceivably you could over-heat it and blow the building up. There is also the possibility of back flow protection on a system where you're using treated water. This is in the present code, so there shouldn't be any substantial problem. As far as heating codes are concerned, there is really nothing covered too thoroughly. We probably would call the piping from the solar unit "brine piping," but all the heating code says is you have to take a hundred pound pressure. So you get some good strong bamboo and you're all set. This is leading up to something pretty soon. The electrical code says you put in UL approved components and you put in the conduit which is required and so on, and you can put in a nice solar unit with probably no special approvals anywhere: you just go ahead and put one in. Okay, now we have all high class engineers and we've all designed systems perfectly, and installed them perfectly with reputable contractors and so on, and we never have to have a code on solar heating.

Now we leave the dream world and we get down to the competitive world. Okay, so the first thing we've got, they discovered they can use an extra thin, an extra chintzy material. Then they find out they have to get on this roof to get to the equipment and they put the equipment on a 90 degree angle and nobody can get to it. So no doubt after the first repairman falls off or gets injured, they'll say you must have a permanent ladder to the equipment with a cat walk and so on. Now you'll get this suoer efficient unit which gets real hot. They'll say will it burn up the roof? Soo.er or later we may have a fire. Once we have a fire, we'll get all hot to say, well you have to have a certain clearance from the roof, or something. These are two things I can think of. There are not an awful lot of things that would be likely to happen.

Then the energy bugs are going to get after us, and they're going to say, you inspectors have nothing to do, why don't you set up standards for efficiency? Now right now we have some efficiency standards; AGA s efficiency standards, UL has safety standards. We only enforce the safety standards of AGA, we don't enforce the efficiency standards. The pendulum did swing towards no regulation and don't worry about the consumer. Now it is swinging to worry about the consumer and worry about efficiency. When the pendulum gets to a certain point, they'll say, let's adopt standards which say the solar unit nas to be at least 40% efficient or 60% efficient, and has to be constructed of such and such "good" materials. When this happens, they'll adopt a standard and somebody will start approving them and say you have to meet the ASHRAE standard or somebody's standard. Right now we don't have it, but it's possible that we will have it someday, and maybe someday the pipes on your roof might leak and will get water on the ceiling of a politician's house and he'll say let's have a law that says you have to use such and such a protective device.

There are a lot of these things that may never happen, or may happen. Like I say, we don't particularly want to have senseless regulations. Until they're forced on us, we probably won't have them. The codes presently are probably open enough so that you can put in a solar heating system just as they are, but I can see, ultimately, various problems develop. They'll probably adopt codes which will help protect the owner against the law of supply and demand, since the contractors and manufacturers will bid against each other and the only way to get the job is to make it cheaper and the only way to protect the consumer is to have standards. So ultimately, we'll have standards, and probably we'll have codes. The answer now of course is there are almost no restrictions. The answer ultimately will be that there will be certain restrictions which all will be sensible (I hope), and I think this will answer the present questions.

QUESTION: What role can major urban communities play in the implementation of diffusion of solar technology?

Response by

Abraham J. Falick

City of Los Angeles

The most intense discussions of solar energy have been taking place between the Planning Department and the Science and Technology Office of the Mayor's office, where we have some very good aerospace engineers. As you know aerospace has been involved in solar energy for a long time. My particular interest lies in two areas. That is, in housing and economic development. And of course, the city has its particular interests in the reduction of fuel consumption. We've gotten very good publicity on our paying $24./barrel for oil from Peru. I hope we don't have to do many more purchases of that type. We'd like to reduce our fossil fuel consumption as well as the pollution that comes from the fossil fuels. Now one of the figures we hear is that 15 to 20% of our energy can come from solar energy by 1990. That sounds like a very interesting goal for us. We happen to have a built-in mechanism to work with. We have the largest municipally owned public utility in the United States, the Los Angeles Department of Water and Power, and we anticipate working with them. We have a mayor who is noted for taking a leadership role, and we expect that we will be taking a leadership role in this area as well. We look at this as I said from the housing and from the economic development end. Now we know, at least we suspect, that we're not going to be putting solar energy into our housing - certainly our single family housing units as yet, and we look at it as starting from the top down. We will be starting with public buildings, using them as our solar test bed, to the extent possible, and working our way down to commercial buildings and apartment buildings, and eventually the single family home.

Now, I should point out that Los Angeles is a fairly large area. We have 464 square miles in the city and we have about a million housing units. Over 50% of the existing housing is single family, but as of last year over 90% of the housing units that were built here were multiple units, apartments and condominiums. We look to the apartment house in the housing field as being the natural way for us to go as far as experimenting and we anticipate the city should take some leadership role in the experimentation. We feel that we also have a great pool of technical talent in the Los Angeles area which has some solar energy experience. We feel this is an employment booster and since we've been losing a lot of jobs, we just don't want to go down that path without giving it a try in the solar energy field.

We do anticipate plenty of problems. Many of them have been discussed here this evening. The institutional problems, the political, social economic, the aesthetic problems. We don't intend to minimize them and as an economist, I'm accustomed to putting dollar signs on a lot of our problems, so that will be part of my job to see where these costs are coming in, and also to propose ways of stimulating people to use solar energy by providing some type of incentives in a form of tax rebates or by simply avoiding the tax on a solar energy unit as it's put on the house. The property tax addition could be a disincentive to put one on. There might be typical steps to take if we are committed to the policy of encouraging the use of solar energy and as I say, I'm not speaking for official policy of the city as yet. This is the type of talk which is still staff discussion; it can't be labeled as the official policy of the city. All I can say is that we're as interested as any city can be.

The city of Santa Clara, northern California, has gotten the jump on us. They are putting in a solar energy unit as a basic component for water heating in one of their large public buildings, with the cooperation of Lockheed. We feel that this is in the direction of which the city of Los Angeles should go as well, and this is the kind of recommendation that we as internal staff people are making. We feel the city and other large cities should take a leadership role in this field.

Diffusion Panel Wrap Up #1

Richard Schoen

UCLA

The list of questions put to the Panel by Sydney Sternberg was preceded with the following context statement:

> "The distance between the essentially engineering/research prototype now existing in solar technology and the advent of commercial, off-the shelf-systems is as at least as long and risky as it is exciting. The purpose of this panel has been to discuss at least some of the questions which will have to be answered along the way."

I believe that it's important for all of us working in this field to realize the extent of that distance, and the kinds of steps which must occur along the way. More important, the media and the public should understand that distance. We often hear the phrase; "solar energy is an idea who's time has come." About four years ago the phrase was put a bit differently. Then, it was, "industrialized housing is an idea who's time had come." Nowadays it is said, "industrialized housing is an idea who's time has come and gone."

Solar technology does not necessarily present an analogous situation, but unless the public is fully appraised of the difficulties involved...of the risks associated with commercializing a technology in the U.S. Construction Industry, solar energy could face a similar situation. There is reason to be concerned that public disillusionment could set in if promises are made for this technology which are unrealistic in terms of performance, real costs, time to market penetration, etc. Hopefully we will see and perhaps participate in the development of solar technology as a viable commercial industry; as a healthy, reasonable process, and that systems are not introduced to the market which fail to live up to promises which they cannot meet from the very beginning. We heard of some of the required steps to achieve that objective in the responses of the panel this evening. We heard them first in terms first of the manufacturer-marketing questions, and it became clear that industry more and more is concerned about being assured of a market because the kinds of requirements of the market in terms of product reliability are becoming essential questions. There are discreet steps in making that decision but most of all it's an expensive decision to make. Even within the industrial community that will make those decisions, there are different world views of how it will occur, depending on whether you're a marketing man or an engineer.

It's complicated even more in terms of communication by having to deal with what is the real or at least short term market. I'm referring to the designer specifier. He needs to be assured of a whole host of basic practical questions before he's going to take the professional risk associated with specifying a new system. And those of us who are in professional practice know what professional risk implies. In the end though, it remains the initial short term consumer who must be convinced and with whom we must also communicate. In the residential market of the builder developer and his subcontractor, we architects may be involved in the design process but mechanical engineers are not involved as often as they should be. In the commercial, institutional, and industrial markets, it is the engineer and the architect as materials, systems, and equipment designers and specifiers who must be communicated to. In the past that has been a rather serial process. However, I think the day is fast coming when the architect will no longer be able to develop his conceptual scheme and then give it the engineer to figure out "how to hold it up and how to heat and cool it." If we're talking about energy conserving design and implementation of new ener y technologies, we're going to have to start talking about real team processes. That means architects have to go a long way towards understanding what ngineering is about, and quite frankly, the engineer has got to come a good distance in the opposite direction. But then both of those people as well as the builder developer, the engineer architect specifying team and the building owner in commercial ventures - must all be convinced that the final user (in a case of housing, the home buyer or renter; in case of commercial buildings, the building user) is indeed interested and believes in this technology. It eventually comes down to the point where perhaps the final user must be well understood because in the end he is the market generator and his value systems are going to be paramount in the decision as to whether or not market penetration is actually achieved.

Associated with these perceptions by the intermediate and final users are not only economic questions, but institutional questions, and social questions as well. As an example of the latter we are in an age now of community resistance to almost all forms of development, after the Livingston and Blaing report which recommended that the City of Palo Alto put a major segment of its foothill land into park land rather than allowing development, as a cost attractive measure. Various kinds of approval resistances against land development and construction, have sprung up in almost every community in the land. In addition we have environmental impact statements and the California Coastline Commission, the difficult but serious child of the Proposition 20, the coastline initiative. What kinds of impact does that have on the intermediate and final consumer in terms of their willingness to utilize new, resource conserving technologies in order to allow some form of development to procede? This question we've asked and yet have not been able to answer. What then is the "market impact of environmental impact" on potential penetration of solar hardware systems and devices for buildings?

There is one useful tool in the process of commercialization which if it's done properly can begin to address many of these issues: that is the demonstration project. I think it's very clear from what we've heard tonight that the demonstration project has got to be viable in industry terms. We're not talking about a model home here, we're not talking about a "House of the Future." We're talking about demonstrations which perhaps are regionally based to reflect the regional character of the industry; which utilize all of the key actors in the process: the subs that would be normally working at that level, the engineer, the architect who would be involved, and the builder developer. Demonstration need not necessarily be big or splashy, on a national scale. They do have to be viable in a given market and for a certain building type. Then industry communications mechanisms which exist can be used to get the results out, and the results have got to be honest. The differences between a demonstration project and a marketing effort have to be recognized. I'm not saying a marketing effort is dishonest, but in this case if you're trying to make industry participants aware of this new technology in all of its ramifications; if you're trying to achieve what we've been calling the diffusion of commercial readiness, then the key actors we've been discussing have got to be given the full story, - the actual results of a demonstration project at whatever level of success. The industry environment is continually changing; fuel costs are continuing to rise. If the demonstration proves a particular version of solar technology is not economically competitive now, admit it. It should be fully disclosed. In a short time it may be. But if the facts have not been properly set out, industry disillusionment may stand in the way of widespread acceptance at a later date when that acceptance would be otherwise possible.

In these efforts it has also been made clear that we need the help of not only industry corporations as individual participants but in terms of their associations, as well. The latter are certainly viable communications mechanisms and of course one of the most important is ASHRAE itself. As John Yellott has indicated, ASHRAE has "been there before" with prior experience in technological innovation for the housing and elsewhere in the construction industry which have since become standard practice, ASHRAE has played a significant role in the past and I think it's more than fair to assume and insist that ASHRAE have a role at this point. There are other associations too, such as the American Institute of Architects and other related professional communities.

This evening we have also seen some of the other problems confronting rapid commercialization of solar technologies. There is the issue of local codes. Not only in a given locale but in terms of the many different code bodies which exist in various marketing areas within which a national manufacturer might care to market. Many times the various codes have differing approval processes. Work is being done on code reform. A good bit of it on state level, ASHRAE has been involved in these efforts.

We have seen that there is interest in the technology at a community level, in terms of creating local demonstration projects. In this case, however, it would be in the institutional building market - publically owned city buildings which is quite a different situation than the commercial market of residential structures or office buildings. I think when those demonstrations are created, it should be made clear that it is one thing to build a building for the city; it's another thing to build in terms of risk associated with development in sales of a project.

George Löf pointed out a number of the industry communications media which are available. Unfortunately, it may be fair to say that a good part of the industry does not read the research literature. In fact there are a number of so called consultants, known as "real estate research corporations," which you all know about, who earn their keep by maintaining a lead time of six months to a year on new developments which may impact the industry and who translate technical information into industry terms-that is, in the things that involve industry concerns on a day to day basis. I believe that we should impact not only the research journals, and the professional engineering and design journals but magazines like Professional Builder, House and Home, AIA Journal, Architecture Record. Here again, we must describe the technology not only in a straightforward manner but in terms that are of interest to that readership and their daily concerns. We must demonstrate the implications on building design of solar cooling systems,-graphically, and with charts and data.

There are other issues which have not been represented here, in this evening's panel which will have considerable impact upon the rate of commercial diffusion of solar technology. For instance, a member of the skilled trades should have been on this panel. We tried, but did not have enough time to line up that person. I'm sure you realize that the skilled unions have everything to do with the way this technology will or will not be implemented. It's probably safe to say for solar thermal systems there will not be abnormal kinds of trade jurisdictional arrangements required other than that are set up with existing industry elements on a regular basis. However, solar photovoltaics involving perhaps a combined collector generating electricity and producing hot water, then the plumber and electrician may end up eying the same unit.

DIFFUSION PANEL WRAP-UP #2

Jerome Weingart

Caltech EQL*

This particular session has been so dense with interesting information that I think it's hard to give a complete summary. What I'll do is touch on major points that came out. I'm excited from a personal point of view about this session, because Dick Schoen, Al Hirshberg, Marx Ayres and I have just finished a study for the Energy Policy Project concerned with institutional problems of implementing new energy technologies, including solar, in the construction industry. We now have new data and comments to add. One of the problems of doing a study like this is that events seem to have overtaken the research. With regard to institutional issues, I'd like to add two to the ones discussed and then put all of these in the context of a review.

Contrary to what some people have thought in the past, solar energy applications, at least on a very large scale, are not free of environmental impact. We have not discussed this issue tonight. I think it's fair to mention that in considering a very large scale industry, perhaps a multi- billion dollar a year solar energy industry by the mid-eighties, we would certainly have to look at the total environmental impact of getting all the material resources out of the ground, whether in this country or elsewhere, and the impact of extracting, smelting, transporting and using all of these materials, and the associated energy and capital requirements. The environmental consequences of a large scale industry will have to be examined. Under NSF sponsorship such a preliminary technology assessment is being conducted at the Arthur D. Little Corporation.

A second issue not discussed tonight has been researched by Dan Dawes of the UCLA law school. That's the question of urban sun rights. I received a call just today from somebody who's interested in putting up a large office building in Pasadena and they want to cover the south wall with collectors. Aside from all of the unsolved and undefined technical problems associated with south wall collectors on a large building, I had to raise the question: "what is the land directly to the south presently zoned for?" It turns out that other high rise buildings could go up and the legal status of a person with collectors who gets his sun shut off three years later by another building, has not been well defined in the United States. I won't bore you with the charming details of English Common Law; they are not adequate to define this area of interest in the United States. For those of you who are interested there will be in the UCLA Law Review, a very comprehensive article by Dan Dawes, who did this study while part time staff member at the Environmental Quality Laboratory.

Let me now mention a few of the what I see as major points that came up tonight.

One of the first is that the total costs of going to market with a new high technology product are large. A study done about ten years ago by the Department of Commerce indicated that the total costs of going to market; the establishment of production facilities, marketing operations, distribution systems, (or tapping into the existing ones), training of personnel and so

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forth, run anywhere from five to ten times the cost of the technological development of the product itself. For these reasons, the commercialization of this product will require that the committments of industry are going to have to bervery large. We heard tonight that going to market with a solar cooling system as a total industrial activity could be in the range of ten to twenty million dollars; perhaps more. That means that before major industry is going to commit, there must be a great deal of ground work in prototype hardware development and demonstrations on real buildings, built by the trades under widely accepted practice, along with verification of the performance of solar systems.

A second point that came up is that although one can immediately design and build total HVAC systems with available, industry acceptable solar collectors, such systems are likely to be more efficient and perhaps more cost effective, if modified versions of related equipment such as absorption chillers are also developed. Thus, there are implications for the development of additional components of the HVAC system. A point that Bill Fleming made, and others alluded to, is that there is a great need to do both the technical development, and market analysis and research, simultaneously and interactively. For example, two different designs of a solar collector may perform identically under laboratory conditions... even under prototype building conditions, but if one of them requires three times as much plumbing as another, with copper pipe installed at $1./ft. and insulation at another $1./ft, the economics of the actual installed system may look very different, even though the performance and the cost per square foot of the collectors themselves may appear essentially identical. By looking carefully at the nature of different markets, the technology can be designed to be economically optimum and performance-optimum <u>before</u> it goes to market. It's very important that, in this sense, engineering and market analysis be done together. I'm told that even in some large companies, the engineering and marketing people often don't communicate well with each other. In the area of solar energy applications such communication is going to be critical.

A third point that came out several times is that in order for this technology to be widely used, it's not enough to have a suitable product and engineering data. That data must be put together in the form of handbooks or, as they are often called, "cookbooks", which can be used by the practicing/contracting/specifying/industry. It's unlikely that the solar energy industry will change the whole construction industry; rather the technologies must fit into existing practices and approaches to the design and construction of buildings or the rate of acceptance of solar hardware is going to be considerably less than it might otherwise be.

It was indicated that the utilities have a key role to play because in the diffusion of solar energy systems on a very large scale, we're certainly talking about (at least for building applications), solar technologies as fuel savers. In that case we're always hooked to a utility grid. Certainly the utilities are going to be concerned about the impact of a large number of small energy producing systems on individual buildings on the total operation of their system.

Finally, although this certainly is not the end of all the things we might say, I think it was quite heartening to see that ASHRAE will be taking an agressive role in providing an information link between R & D in the field, in the field and the industry which is going to be using the hardware. This is a crucial link and I'm delighted this will be happening. In summary, this is one of the very few times that this kind of assembly, people representing industry, utilities and other in the real world of applications, have come together to provide coherent expositions of various problems and approaches that have to be addressed in the large scale commercialization of solar energy conversion systems. I think it's been very useful for all of us.

Commentator: Sidney Sternberg

NSF

Questions and Answers:

Sidney Sternberg: There is one question from Arnold Lesk, Motorola:
The question to be posed to utilities-the concept of a capacity plus usage formula seems to violate the concept of energy conservation. I believe the charge of energy is larger for the small user. Is there any other option?

Papay: I don't know if it would be a penalty for small users. Actually for most or all utilities, the rate structure as designed does penalize the small user. When I spoke of a capacity and a usage rate structure, I was rating that as a possible alternative. The point is, if you're looking specifically at cooling applications with electricity as the supplemental energy form there's a fairly good degree of coincidence between the solar energy peak and the peak demand for air conditioning. Also you may find that capacity factors for central station generating plants will be higher. In other words a greater portion of the load can be considered to be base load with a smaller peaking load. Consequently, you may find just the reverse situation exists than that implied by the question. I'm not advocating any particular rate structure, I'm saying that the question of rates would have to be looked at. The interaction between a solar system and a supplemental energy system, whether it be electric or gas, will have to be looked at. That's all.

Anonymous Questioner: Question posed to William Fleming and Jerome Scott:
Why do you assume that consumer acceptance is necessary for implementation of solar systems? Seat belts and auto emission controls have had very low consumer acceptance but are in all new cars. Why can't we implement solar energy by government regulation or excise taxes on fuel? Can we regulate solar energy into being?

Scott: That may be done and I'll give you an example. There's one state that currently has before the Assembly a performance specification. AISCE; an intersociety liason committee on the environment, on which I am the ASHRAE representative, gave its technical opinion that the performance specification should state that if equal to or less in capital and operating costs (including maintenance) and equal to or greater in performance ability, all public buildings will utilize solar and cooling heating. That is one state's pending legislation, so it could occur. However, I have a hunch that there will be a mass transit of current suppliers of other equipment to the state Assembly and that bill will not pass.

Sternberg: There is a gentlemen who looks to be in desperate need of solar energy. He claims our propane costs have doubled in two months and would like to know what hardware will be available to heat and cool mobile homes at Grass Valley a year from now and what the capital and operating costs would be. Would anyone care to answer that question?

Answer by Sternberg: As was mentioned before, we do have a demonstration mobile home under test at the present time. We do have a preliminary small shop for making collectors. I don't think any decision has been made yet on going into full production on this but, it's not saying that we wouldn't undertake the thought at a later time.

Sternberg: The next question is to the National Science Foundation. In evaluating performance of a solar cooling and/or heating system the design of the building for energy conservation will be an important consideration. Will this aspect of NSF Programs be explicitly analyzed and reported?

Answer by Sternberg: There is a very specific program of the National Science Foundation relating to conservation of energy. As a matter of fact, if you're interested in hearing more about it, Bill Whetmore who is the director of the office of systems integration analysis is working on energy conservation and naturally has been granting to various organizations studies in the energy conservation area. So if you're interested, please get in touch with Bill Whetmore. There is a very specific and very active program in energy conservation.

Joe Spirch, H&S Engineering: I want to direct this to William Fleming about acceptance by the people of our nation. Ten years for the general public for homes, is that a reasonable number if we come to a very vital crisis in our energy situation?

William Fleming: The ten years that I was talking about assumed the present rate of energy consumption and 1985, 1986 is where the supply deficit occurs. It also assumed that Nuclear Power Plants would be in existence in the mid 1980's and that the oil embargo would not continue. The actual consumer himself is not the particular party that will have to accept. The entire marketing system must accept. The marketing system consists of the architect, the consulting engineer and finally the investor developer; if we're talking about commercial construction. If we're talking about residential construction, the solar system technological and market development must include the architect and the developer and the contractor as the market system. Those are the people who are going to have to accept solar systems and they'll accept it only on a profit and performance basis.

Stan Kellman, State College, Pennsylvania: This is more in the way of a comment than a question, but I detect, first of all a note of pessimism in this audience, but I don't think it's all that bad. I'd like to point out the fact that a heat operated machine like an absorption machine is collecting solar energy from the sun, and the thing is troubling me a bit is that we're talking in terms of products. First of all I don't think you can segregate products from systems and you can't segregate heating from cooling, because a commercial office building system will have an interior zone cooling load year round, and it will have an exterior heating load and here you've got a solar energy system say absorption or some other system, therefore, you can do the cooling year round, and you have heat available for the heating. All you have to do is place that around the building and you can do that with technology that we now have available. So that I'm just pointing out the fact that I think we ought to think everytime in terms of a heating and cooling system, one system, and I think we can make this thing go. Finally, I'd just like to say, as a member of ASHRAE, I'm pleased to see so much interchange of information because we haven't had this for so long. It's great to get NSF people and solar energy people together to get this technology into the literature, where it will be used by practicing and consulting engineers. You can hear that through the audience tonight how badly they want it.

Wellesley-Miller, MIT:
I've noticed again that note of pessimism that we have blue sky optimists and grade A pessimists. I prefer to stick with about 50% cloud cover usually, which is the national average, but today I'd like to be more on the optimist side. We have a couple of things that have struck me in the discussions today. One is, that nearly all of the development has been oriented towards hot water systems. I don't know why. They're much less reliable. They require much more off-the-shelf technology. The only reason I can think for it, is that they do require industrialization in a big way that could be taken care of by large firms. It seems to me that if we are going to get a lot of solar energy used quickly, then we need to design for the people who make buildings. In that sense, hot air systems which use no new technology, not already available, and which can use the normal materials, available from building materials outlets that are already there all makes far more sense for low rise buildings. Hot water systems start to make sense when you go above one or two stories because the hot air systems are limited by the noise when you're using high air rates on the one hand and limited by the size of the ducts on the other. I wonder why there hasn't been more emphasis on that. Also the same remark applies to an approach that's been demonstrated this evening at least to solar cooling. I do not think we have gotten to absorption cycles as yet in this workshop but I've heard that there are no discussion of anything else except absorption cycles when we're talking about technology and implementation.

Newton: I think it's fair to say that in the comments that I made at least as a cost of getting into business, I wasn't thinking of any one system the same remarks would apply if you're going to develop special equipment whether it's an absorption system which may have some real advantages or a Rankine cycle. I don't think we're specifically saying that it had to be a water system. There are air systems. We probably will hear more about them as we go further with the program.

Sternberg: One thing also that wasn't mentioned that might reply to that question is heat pump systems. They're in existence today, and they can be applied to a solar collector very easily. Well, I'd like to end on the note of optimism which you offered us. It's going to be a hard row to hoe before we get there, but I think we have the people, the interest and the technology to make it. I would like to thank on behalf of NSF the ASHRAE organization for making this meeting possible and allowing us to get together with your organization. I would like to personally thank the panel members for their thoughtful and thought provoking remarks and I would like you the audience to acknowledge that at this time. The meeting is adjourned.

SESSION II - ABSORPTION AND HEAT PUMP SYSTEMS

Session Chairman: Charles Chen

THE COLORADO STATE UNIVERSITY SOLAR HEATED AND COOLED HOUSE

George O.G. Löf

Colorado State University

Introduction

I'd first like to mention the general structure of our project. This is a joint effort between a number of people and several institutions. This work first involves my colleagues at Colorado State University: Dan Ward, Charles Smith, John Ward, and several graduate students. The University of Wisconsin is a partner in the project. The main input from that institution, with Jack Duffie and Bill Beckman, is the mathematical modeling of the house and the heating and cooling system, directed toward obtaining an optimum design, and later in comparing the predicted performance with the actual performance. Honeywell is a partner in the project with the supply of the control system and the engineering of the controls, with Lorne Nelson, Roger Schmidt and Dave Sutton. The architects for the house, Crowther, Cruse, McWilliams, are responsible for design of the building. Integration of the heating and cooling system with the house design is essential, and they are also associated in that capacity. Various manufacturers cooperating through the supply of products are: Arkla Industries, Johns Manville, Olin Industries and others. The entire project is sponsored by the National Science Foundation (NSF-RANN).

Solar Heating and Cooling Cooling Costs

If solar heating and cooling costs could not be expected to become competitive, a project of this sort would be largely an academic exercise. So I'd like to present a summary of an economic study that was done by Dick Tybout and myself showing the position of solar heating and cooling insofar as costs are concerned. This project involved computer modeling, of weather data from a number of places in the U.S., evaluation on an hour by hour basis of the amount of heat which the solar system provided to the heating load and cooling load (cooling via a lithium bromide absorption machine), evaluation of the amount of auxiliary fuel needed, trials of a number of designs in each place, and a seeking of the design which produced least cost solar heat.

This analysis requires assumptions of the capital costs of the system. We chose \$4./sq. ft. as a near term collector cost, and then we added reasonably firm capital costs of storage tanks, control systems, and auxiliary units. We also chose \$2./sq. ft as a collector cost as representing a "down-the-road" possibility. This \$2./sq. ft. figure would require a design which would permit trading off some of the collector costs with savings which could be achieved by eliminating a part of the roof cost. The \$4 and \$2 costs are debatable, but the numbers I'm going to show are based on a \$2./sq. ft. assumed collector cost with a 20 year amortization at 8% interest. We chose eight cities and obtained from the National Weather Records Center, hourly values of dry bulb and wet bulb temperatures, solar radiation, solar position and wind velocity. With those values for these cities, Santa Maria, California, Albuquerque, Phoenix, Omaha, Boston, Charleston, South Carolina, Seattle and Miami, we programmed the data with models representing the performance of the solar collector and solar storage system, and on an hourly basis computed the amounts of solar energy supplied and the amount of auxiliary supplied with the parameters used in the design. Two house sizes, a 15 thousand BTU per degree day house and a 25 thousand

BTU per degree day house (for heating), several tilts of the solar collector, several number of glass cover plates, several collector sizes, several storage sizes, and a couple of other minor design variables also were tested.

The solar heat recoveries were totaled on a semi monthly basis and finally on an annual basis, for each design in each location. A typical set of results is shown in Figure 1 for Albuquerque in which the costs of solar heat (solar heat only, exclusive of auxiliary) is plotted as dollars per million BTU, as a function of collector area for one of these typical houses. Notice the curve for heating only, applicable to a house with no solar cooling system. The collector size optimizes at a fairly small area, around 300 to 350 square feet. At that point about 57% of the heating load is carried by solar energy, as indicated by the number on the curve, at a cost of $2 per million BTU. With a larger collector, more of the heating load can be carried by solar, but at a higher cost. This is because the larger collector is operating at a lower load factor. For cooling only, we have another curve. The collector optimizes at nearly 1,000 square feet, carries about 70% of the cooling load, and would do so at a cost a little over $3 per million BTU (under these assumptions). If both solar heating and cooling are employed, solar energy costs are reduced because the collector is being used virtually all year round instead of in only one season, and the cost minimizes at about 600 or 700 square feet and $1.60 - $1.70 per million BTU. For cooling, a $1,000 penalty was assessed against the system for the additional costs a three ton absorption cooler over a compression cooler. Again, these numbers are based on certain assumptions which will have to be verified or modified with experience.

If solar heat costs are plotted against the amount of storage, Figure 2, the rather flat curve for cooling illustrates a point one of the speakers made last night. Not much storage is needed for cooling because the load pattern matches the supply quite well. For heating, about ten pounds of water per square foot of collector shows lowest cost; with larger amounts, there is a small increase in cost, because the additional cost of the storage tank is slightly higher than the additional fuel saved. The combined system has a very flat optimum between about eight or ten pounds of water and about twenty pounds.

Solar heating and cooling costs in the eight locations are shown in Table 1. The least cost solar heat design in each city is shown. The collector size for a 25,000 BTU per degree-day house, the percentage of the heating load carried, the percentage of the cooling load carried and the percentage of the combined load carried are indicated for each location. Comparisons of these solar costs with conventional sources in those locations in 1970 are shown in Table 2. In each case the solar is more expensive than gas. In Miami, solar heat is a little cheaper than oil, and in all cases, cheaper than electricity. The present costs of propane and oil, 30¢ to 40¢ a gallon, are equivalent to $3 to $4 per million BTU actual heat delivery.

Solar Heated and Cooled House

These results show why we're interested in solar cooling as a supplement to solar heating. We think the economics are sufficiently attractive for a concerted effort to develop solar cooling. So, we are starting construction of the first completely integrated system for solar heating and cooling. It will be a solar heated and cooled house, shown in Figure 3 having 1500 square feet of living area and a 1500 square foot heated basement. It is of typical construction, with normal insulation and double glazing. It has a collector area of about 720 square feet on the south sloping roof at 45 degrees. We expect to have it in operation by early summer. The purpose of the project is the design, construction, operation, and evaluation of this integrated system for solar heating and cooling.

Figure 4 shows the recovery of heat in a solar collector in an anti-freeze solution. This liquid is pumped through a heat exchanger where heat is transferred to water in an 1100 gallon storage tank. House hot water is supplied also by heat exchange. On call from the thermostat, hot water is pumped from storage via the auxiliary boiler to a heating coil, through which house air is circulated; the water is returned to storage. The system also provides cooling via an automatic valve which directs the hot water to the generator of the lithium bromide absorption cooling unit, returning to storage, while house air is circulated through the cooling unit.

System Details

Figure 5 shows how the collector supplies heated liquid through a heat exchanger, down into a sump tank to the pump and back to the collector. Ethylene glycol in this solution prevents it from freezing in the cold Colorado winter. There is a second loop in which water from storage is circulated through the heat exchanger back to storage, thereby delivering heat to the storage system. Figure 5 shows details of this design. Several flow arrangements permit testing different schemes of operation. One summer alternative involves circulation from collector directly into the storage tank and back to the collector. This will avoid the temperature drop through the heat exchanger. If we find that the collector does not hold up any water, we may use this flow pattern even in winter. Freezing in the collector is a considerable hazard, so we're going to use the heat exchange system first.

The stored heat can be used in the house in a number of ways. Figure 6 illustrates its use when the house is heated by the storage tank. Water is withdrawn from the top of the tank (there will be some stratification in the storage tank), pumped through the air coil through which house air is circulating; water returns from the coil to the bottom of the storage tank, the pump being actuated by the house thermostat. This would be the normal circuit for house heating. If the load is being adequately met, as indicated by the direction of house temperature change relative to the thermostat setting, fuel is not used. If house temperature decreases another degree or two, the auxiliary will go on.

Solar cooling directly from storage is shown in Figure 7. Hot water flows from the top of the storage tank to a selector valve which directs it to the lithium bromide air conditioning unit. Heat is thus supplied to the generator of the air conditioner, as the water returns to the bottom of the storage tank. House air is circulated through the 3-ton air conditioner at a rate of 1200 CFM. Hot water temperatures range from 170 to 195 degrees F. Water cooling at the absorption refrigerator requires use of a small cooling tower. We also plan to operate the cooler directly from the collectors without going through storage. This loop, shown in Figure 8, involves delivering hot water from the collector directly to the air conditioner and back through the pump to the collector.

When the water temperature in storage is not sufficient to operate the absorption cooler, the auxiliary heater will be employed rather than the water in storage as shown in Figure 8. When the house calls for cooling the auxiliary pump then circulates hot water from a conventional boiler to the air conditioner and back to the boiler. This would be the conventional operation of an absorption cooler by means of a fuel heat supply.

Shown in Figure 9 is one of the circuits used for heating the house when stored heat is insufficient to meet the full load. In this operating mode, the house thermostat is actuating the system which delivers hot water from storage to the duct coil, supplying what heat it can.

Even if storage is only 90 degrees, some heat can be supplied to the air circulating through the coil; and at some times that temperature may be adequate, as in mild weather. But in cold weather, a second contact on the thermostat will actuate the auxiliary heater and pump, circulating hot water through a separate duct coil immediately following the solar coil. The heat thus supplied serves as an air temperature booster.

Figure 10 shows the use of solar heat to provide service hot water by heat exchange with the main storage. Hot water is circulated from storage through a small heat exchanger by a pump. Cold water is supplied to an 80 gallon tank from which it is circulated by a pump through the heat exchanger and back into the 80 gallon tank. Water from that tank then passes to an ordinary gas fired automatic water heater when hot water is used.

In a fully developed system, the heat exchangers could be in the form of pipe coils directly in the storage tank. Two pumps could then be eliminated and thermosyphon circulation from the service hot water solar tank would eliminate a third pump. However, in this installation we want to be able to repair leaks if they occur and to measure temperatures of all streams, so external heat exchangers are used.

In the solar collector, an anti-freeze solution will be used unless experience shows the system will drain completely. This fluid is circulated through an aluminum roll-bond panel, 3 ft. by 8 ft. in size, shown in Figure 11. This absorber plate is mounted above insulation laid on top of a sub roof on the building. Two layers of glass are spaced above the roll-bond panel, and a capstrip and gasketing form a top closure. The roll-bond panel is coated with a flat black paint. A manifold at the lower end of the collector feeds liquid in parallel to the 16 pairs of roll-bond panels from which the liquid flows into a top manifold. The connections between the panels and the manifolds are flexible radiation hose. The 16 foot length collector section comprises two roll-bond panels interconnected with "swedge lock" fittings.

Figure 12 is a plan view of a 3 X 8 ft. roll-bond panel. Cross sections of the individual tubes and of the two manifolds are shown. Water enters at the bottom and passes in parallel through the tubes.

The solar heating and cooling system is fully instrumented so that performance can be reliably determined. A 100 channel recorder will receive the signals from thermocouples, flow meters, pyranometers and the fuel supply meters. A magnetic tape will feed these data to a computer for performance evaluation.

Table 1. Solar Heating and Cooling Design Optima

	Collector Area (ft^2)	Water Heating Load (Btu/hr)	Storage (lbs/ft^2)	Covers	% Load by Solar			Cost Combined $ per 10^6 Btu
					Cooling	Heating	Combined	
Albuquerque	521	1041	10	2	56	73	63	1.73
Miami	1041	1041	10	3	58	100	60	2.13
Charleston	1041	1041	10	3	62	92	68	2.47
Phoenix	1041	1041	10	3	29**	100	33**	1.71
Omaha	1041	1041	10	2	57	60	59	2.48
Boston	1041	1041	15	2	66	64	65	3.07
Santa Maria*	260	1041	10	2	27	64	52	2.45
Seattle*	521	1041	15	2	39	44	43	2.79

* One computation only

** Building assumed to have ten times heat exchange rate as in other locations

Collector Tilt = latitude (except Miami = Lat − 10°)

Optimum criterion—least cost solar heat fro combined use

Hot water heating included

Collector cost $2 per ft^2

Storage cost 5¢ per pound of water

Other constant costs $375 per system

Air conditioner cost $1000 above conventional

C.O.P. of absorption cooler 0.6

Amortization 20 years @ 8% interest

Building heat load, 25000 Btu per degree-day

SOURCE: Löf and Tybout, publication pending

Table [illegible]. Cost of Solar Heating and Cooling, $ per million Btu

	Oil or Gas	Electricity	Solar Heating	Solar Cooling	Solar Combined
Albuquerque	[illegible]	4.63	2.07	3.27	<u>1.73</u>
Miami	2.75 ([illegible])	4.87	>5.00	2.26	<u>2.13</u>
Charleston	1.14	4.22	3.34	3.50	<u>2.47</u>
Phoenix	0.94	5.07	2.86	2.05	<u>1.71</u>
Omaha	1.23	3.25	2.93	5.41	<u>2.48</u>
Boston	2.04	5.25	<u>3.32</u>	8.74	3.07
Santa Maria*	1.70	4.28	<u>1.57</u>	14.60	2.45
Seattle*	2.20	2.29	<u>3.15</u>	19.63	3.79

* One computation only

Design optima based on least cost solar heat for purpose or purposes indicated (Underlines show minimum solar costs in each location)

Water heating included

1970 fuel and electricity prices, adjusted for 56% oil operating efficiency and 67% gas operating efficiency

Solar costs based on $2 per ft² collector, 20-year life, 8% interest, $1000 surcharge for cooling

SOURCE: Löf and Tybout, publication pending

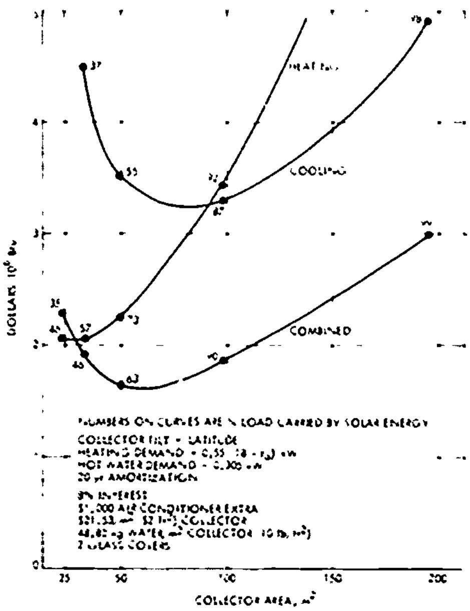


Fig. 1. Cost of Heat Versus Size of Collector in Albuquerque.

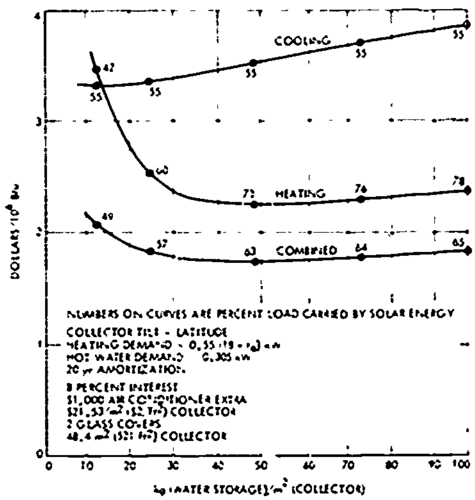


Fig. 2. Cost of Heat Versus Size of Storage in Albuquerque.

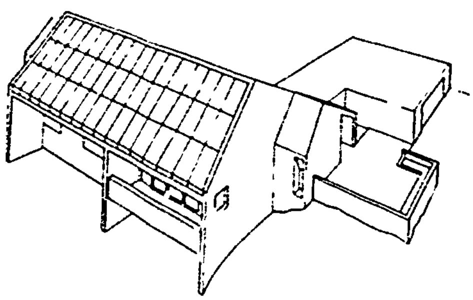


Fig. 3. Perspective drawing of Solar Energy Applications Laboratory Building to be constructed on the Foothills Campus of Colorado State University near Fort Collins, Colorado. This will be the world's first solar heated and cooled building.

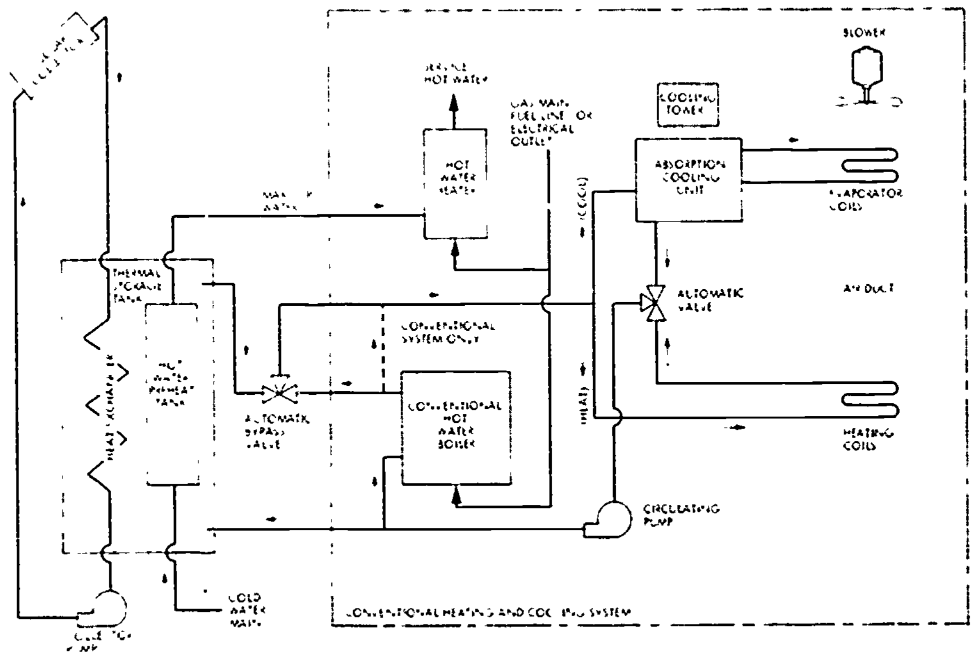


Fig. 4. Solar Heating and Cooling System.

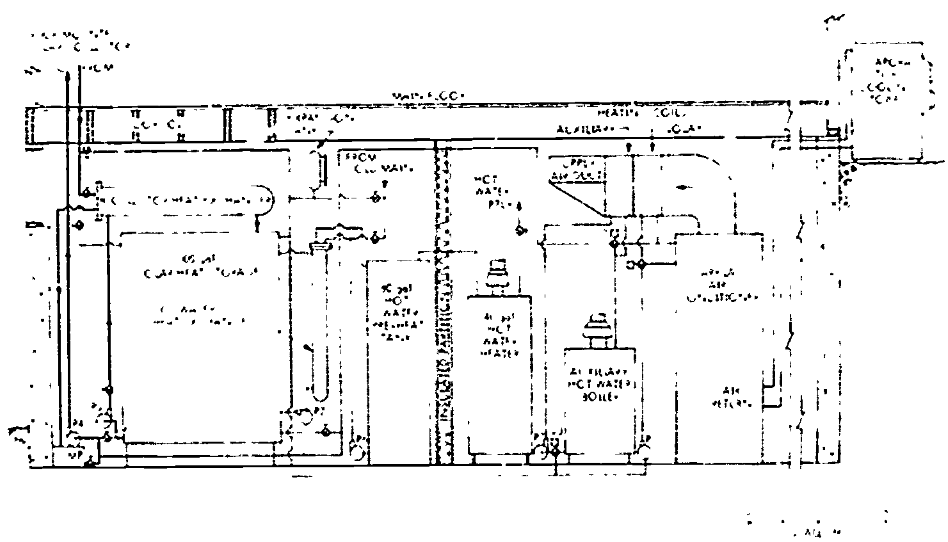


Fig. 5. Solar Energy House
Heating-Air Conditioning-Hot Water Equipment
Mode 1 - Storing Heat from Collectors by Heat Exchanger.

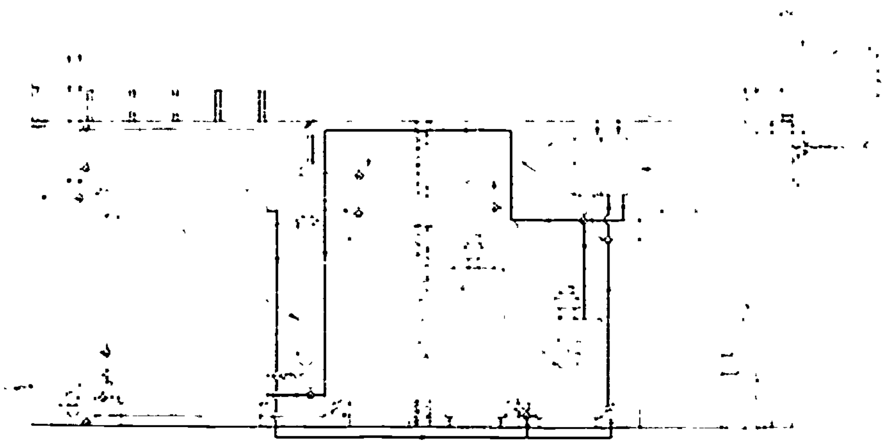


Fig. 6. Solar Energy House
Heating-Air Conditioning-Hot Water Equipment
Solar Heating from Storage Plus Auxiliary Back-up.

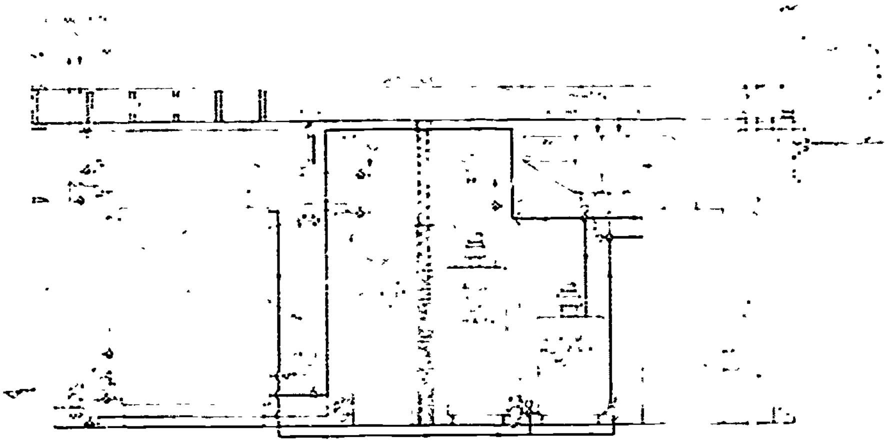


Fig. 7. Solar Energy House
Heating-Air Conditioning-Hot Water Equipment
Solar Cooling from Storage Plus Auxiliary Back-up.

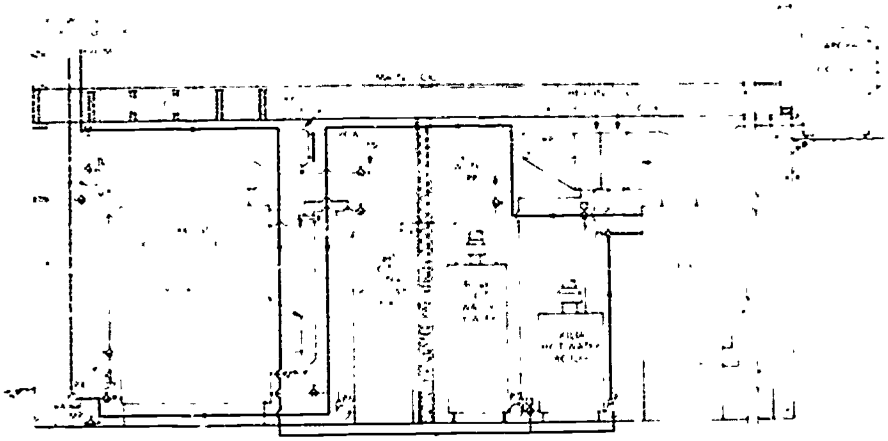


Fig. 8. Solar Energy House
Heating-Air Conditioning-Hot Water Equipment
Mode 3 - Solar Cooling Directly from Collectors.

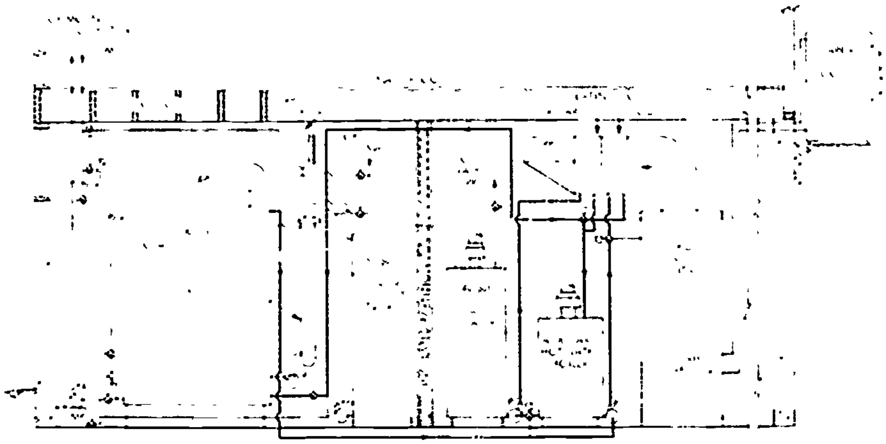


Fig. 9. Solar Energy House
Heating-Air Conditioning-Hot Water Equipment
Alternate Mode-Auxiliary Heating with Solar Pre-Heat from Storage.

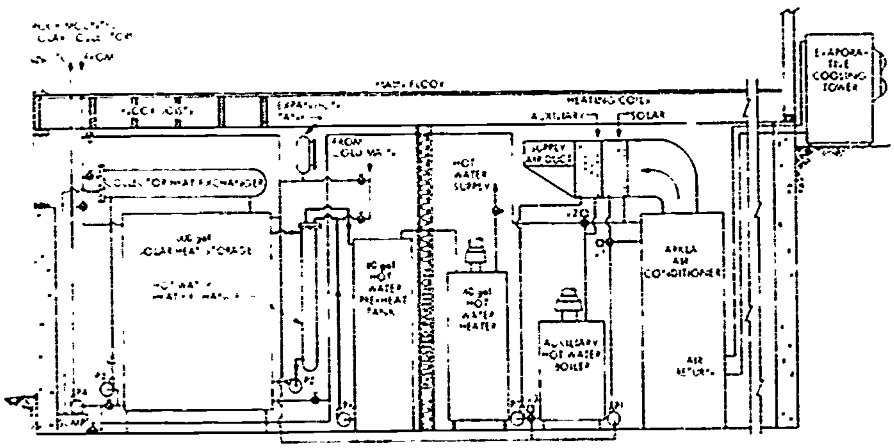


Fig. 10. Solar Energy House
Heating-Air Conditioning-Hot Water Equipment
Solar Heating Service Hot Water.

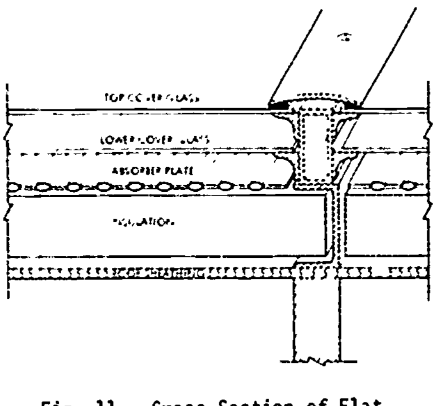


Fig. 11. Cross Section of Flat
Plate Collector.

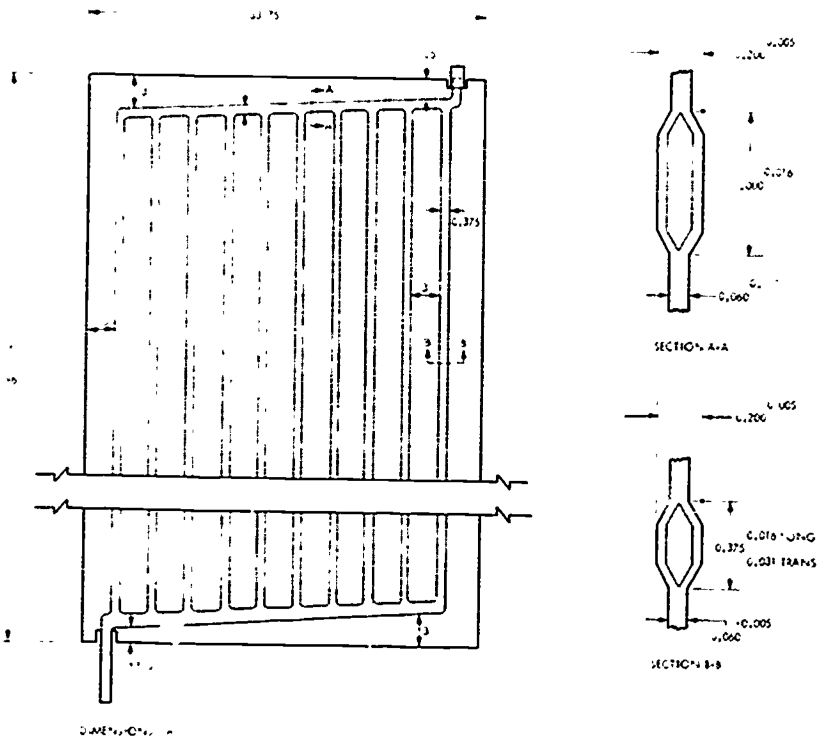


Fig. 12. Plan View of Roll-Bond Panel.

THE LITHIUM BROMIDE SYSTEMS USED IN SOLAR APPLICATIONS

William Beckman

University of Wisconsin

The major problem that we have been working on lately, is the development of a technique to model transient solar systems. Recall some of George Löf's slides that showed the complicated piping in the various modes of operation. We have the problem of modeling this system on a computer. Everytime George decided that he wanted to make a little change, our program had terrible gyrations, and often it would be many months before we would have it running again. About two years ago it was decided the best way to approach this problem is to instruct the computer how to do all of the bookkeeping and numerical integrating for a completely general system. The programmer becomes a plumber or an electrician. All one has to do is tell the computer how the various components are connected together with pipes ar wires.

We have modeled various solar system components. For example, we have a generalized model of a solar collector. We actually have two or three different collector models depending on the detail you want. The user connects together, in a relatively simple manner, the output of one unit into the input of another unit. The program does all of the bookkeeping; it keeps track of mass balances, energy balances, and any integrated quantities you want. To make a change now is a trivial job where before it sometimes took many months.

What I'm going to present · · economics studies by Butz (1973) which were done in the first part of the project using a computer simulation that was of the old fashioned type where it was a special program for a special job. We're in the process of using our generalized program to model this very same system and in addition to model some more of the CSU house. Figure 1 shows the system that we modeled. It is similar to the Colorado State University house, with some minor differences. We have a hot water solar collector which is indicated by the letter A. Our modeling techniques are such that virtually every solar collector can be described with very few parameters. These parameters, as discussed by Whillier (1967) describe collectors in terms of an F' or an F_R, an overall loss coefficient, U_L, and the transmittance absorptance product of the covers. In this study we are using a two glass cover water heating collector, with an F_R of 0.86 and a U_L of 0.8 BTU/hr/ft^{2}F. We have not, in this particular model, included the ethylene glycol heat exchanger loop as in the CSU house which is required if you really need to prevent the system from freezing. Hot water in the storage tank (B) during the heating part of the cycle passes through a heat exchanger (D) which heats air that comes from the building and returns to the building. The cooled water then returns to the storage tank. Whenever this particular system can not supply the total load from solar energy, we turn on an auxiliary heater (E) which could be a gas fired or oil fired furnace. We now have perfect hind sight and we realize that a this kind of a loop was a bad choice. If we do not have sufficient solar energy, and we have to turn on the auxiliary, then all of the energy that the auxiliary puts out is not immediately transferred to the air stream through heat exchanger (D) and the auxiliary supply tends to drive up the temperature of the storage tank, in addition to warming the house. If the storage tank temperature increases, the inlet temperature to the collector increases and the collector works at a higher average temperature which means poorer performance.

The model has a service hot water system somewhat different from the two tanks that George showed in the previous talk. We have a heat exchanger and a single tank (C) which represents a more or less conventional gas, oil or electrical fired hot water system.

In the air conditioning mode, we have a valve which directs the hot water into an absorption air conditioner (H) rather than into the air heat exchanger. Cooling water evaporating coils are located in the air stream, and air from the house is circulated past these coils and cooler air is supplied to the house. The air conditioner was modeled as being approximately a three ton unit. The original model was somewhat optimistic but is more sophisticated than the model orginally used by Löf and Tybout (1973). For example, the performance of this unit depends upon the temperature of the incoming water to the generator and we varied the capacity of the machine depending upon the temperature of this water. If it is at the design condition then the system operates at 100% capacity. At other combinations of cooling water temperature and temperatures to the generator, the cooling capacity varies down to 50% at a minimum (we decided at 50% the system would cut off) and up to 115%. One of the difficulties of the lithium bromide system is that it requires, in its present design state, low temperature cooling which is going to have to be supplied by a cooling tower. We model the cooling tower using a 10^{0}F approach to wet bulb, which is a conservative design. A real system will operate somewhat better than that, particularly when the system is operating at part load.

We realized that in this study it was going to be expensive to do the complete analysis as presented by Löf and Tybout (1970, 1973). Our model is somewhat more sophisticated and burned up considerably more computer time. We tried to include the dynamics of the house more accurately, and modeled the house to include heat capacity effects, changes in the solar radiation and all other associated energy terms in a manner similar to what would be done in designing a very large building. It turns out that this part of the program, which in Georges' case was a small computation effort because it was basically a BTU per degree day house, is a significant money consumer in our program. We chose one site, Albuquerque which is one of the better sites which George had in his study. We also used exactly the same weather data that George used.

The controls work in the following manner. If the system deviates from the set point by 2 degrees, we turn on the solar system. If the house temperature continues to deviate by another couple of degrees, that means solar isn't sufficient and we turn on auxiliary. Our system had a two stage auxiliary heater so that if the temperature varied another two degrees we'll turn on the second stage of auxiliary. The second stage of auxiliary along with the first, was sufficient to meet the worst loads that the system could experience.

Now it's very important that we realize there are a tremendous number of design variables that should be looked at. The most significant design variable of course is collector area, and that's what we concentrated on. We looked at the Tybout and Löf (1970) and Löf and Tybout (1973) results and decided that they had done an excellent job in determining the optimum storage tank capacity. We chose to maintain the storage tank capacity equal to 12 1/2 pounds of water per square foot of collector. We also chose two glass covers which Tybout and Löf said was near the optimum so the only design variable that we are concerned with is collector area.

During our hour by hour simulations we often found that near noon the collector efficiency would be on the order of 50%. I know people who quote collectors efficiency based on noon time measurements and imply that the efficiency of their collector is 50%. As we'll see this a very optimistic way of looking at it, because the collector is part of a system and you must look at the whole system performance not just the instantaneous collector performance.

Figure 2 shows the monthly averages of energy quantities for a collector area of 350 square feet and it shows what happens, for example, to the energy required by the building to keep it warm. In January it's high and it decreases to essentially zero in May, picks up again in October and increases through January. During this time the main auxiliary heater had to supply various fractions of the load. The auxiliary is high in January for this smaller collector and decreases towards zero in May.

When the cooling season arrives, sometimes you have both heating and cooling. In this particular example, for roughly one month (April), the system required both heating and cooling. A control system was designed into the model so that if the temperature decreases down to 60 degrees, when in the air conditioning mode it switches over to the heating mode. If the excursion is very large the other way, at 95 degrees it switches over to the cooling cycle. Also shown on Figure 2 is the energy transfer to the generator of the air conditioner. This is not the actual air conditioning load but is the energy supplied to the air conditioner. This air conditioner was modeled with a constant COP of 0.65 which has been shown by experiments to be a reasonably good approximation. The few experiments that have been done show that the COP is roughly a constant, and that's what we built into the system.

Consider the largest collector area as shown on Figure 3. The efficiency has a peak in January, and a peak in July. The reason for the winter peak is that the system is loaded in January and the storage tank temperature is low. With the low temperature to the collector, the collector works quite well. The same thing happens in the summer time. The collector is working at a low temperature because solar energy is being used for the air conditioner. During the spring and fall, there is only a small load. With the storage tank hot, the temperature supplied to the collector is high and the efficiency of the collector low. You just can't use the energy that's there, and in fact, there is energy that the system actually had to dump. This situation is not so pronounced for the small collector since the service hot water load is large enough to keep the storage tank temperature down during the spring and fall. The important point is that during the spring and fall every solar energy system is going to be over-designed and during the winter and summer it's going to be under-designed.

Figure 4, shows the system efficiency as a function of collector area. The left part of the graph is for heating and cooling with roughly 100 square feet of collector ($15M^2$). The system efficiency is 40% and solar supplies 28% of the load. The small collector maintains a low storage tank temperature. With the low temperature input to the collector, the integrated efficiency is high. As the collector size increases, the amount of that energy that you can actually use decreases. There are longer periods of time when you have excess energy that drives up the storage tank temperature. If the collector area increases from 100 square feet ($15M^2$) to 1,000 square feet ($90M^2$), the average system efficiency has gone from 40% down to roughly 20%. This is a point that is often neglected in estimating the performance of a system. You cannot estimate system efficiency from static experiments. You must really look at the dynamics of the whole system.

It's too bad that this simulation process if so costly, because at present you can't afford to do it for a small residence. A designer can't afford computer time to do this kind of study to see how his design will perform. I believe ASHRAE will come up with some scheme for reducing all the thousands of calculations that went into generating these curves, into something that designers in the field can use.

Recently we asked ourselves, "What would happen to this system if it did not have air conditioning?" We took out the air conditioning part of the cycle, and again looked at the system efficiency. During the summertime, since we took out the air conditioning, the system provides all of the hot water. In the system with air conditioning, only part of the hot water requirements were supplied by solar. Without air conditioning we have a tremendously large collector only supplying hot water and it can meet all the needs. It turns out that for heating only the system efficiency curve drops 10% for all collector areas. At a collector area of 100 square feet rather than being 40% efficient, it's something like 30% efficient if you're just doing heating. At 1,000 ft^2, rather than being 20% efficient, it's about 10% efficient. This is 10% annual efficiency out of a collector that can operate at 50 or 60% noon time efficiency.

We performed some economic evaluations that are really the major purpose of the whole study. Shown on the abscissa of Figure 5 is the collector area, going from zero to $100m^2$. This particular graph is for one particular cost of electrical energy; 3¢ a kilowatt hour. The ordinate is the annual cost above a base cost. The base cost is the cost of all the things that you would have to have in the solar energy system that are also included in a conventional system. There are lots of ducts, piping and a furnace that are required in a conventional system. We also need these in a solar system. A solar energy system costs more because of the collectors, the storage tank, the additional piping and controls and also because the solar energy system requires an absorption air conditioner rather than a vapor compression machine. We assumed extra costs of $1250 for the solar system to cover these costs. We then looked at costs over a year. Shown on Figure 5 are 3 different collection costs of $20, $40 and $60 per square meter. For each of these collection costs we have curves for 3 different fuel costs; $2, $4 and $6 per million KJ. For a collector cost of $20 and a fuel cost of $2 - the cost of the solar energy system starts out to cost $475 a year above the base cost, decreases down to about $380 a year above the base cost with a collector area of about 50 square meters and then begins to increase again. It begins to increase again because the efficiency is going down as the collector area goes up. Now compare this with what the conventional system costs as shown by the horizontal lines. This is the conventional system cost for a fuel cost of $2. You can see for the numbers we've chosen for this house in Albuquerque, a collector area of from 20 to 80 square meters yields a cost somewhat less than the costs of the conventional fuel system.

I would like to conclude by saying that we've shown here an example of what you can do with modeling. Modeling allows you to do experiments relatively cheaply. Our computer modeling of the CSU house costs about $100 for each different design. To build a house for each of these different designs would cost many thousands of dollars. For a small investment we can do a large number of design studies on the computer to gain experience and insight into system behavior.

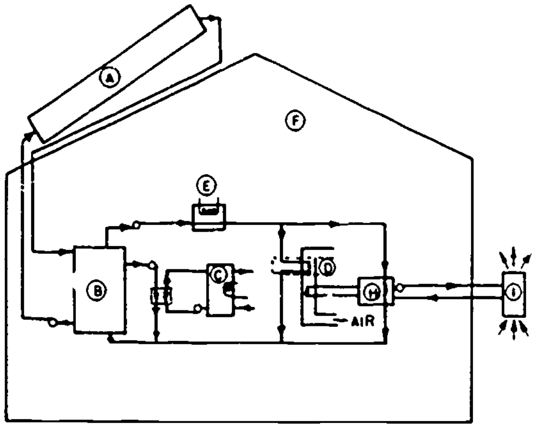


Fig. 1. System Model

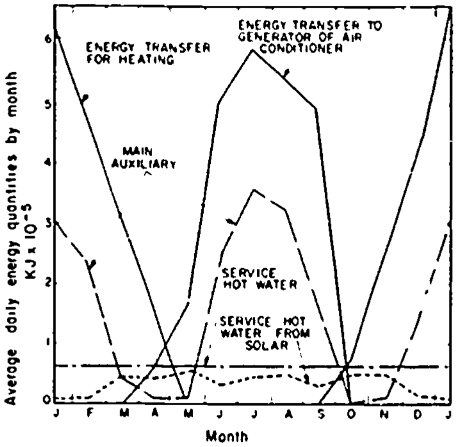


Fig. 2. Monthly Averages of Energy Quantities for a 350 ft^2 Collector

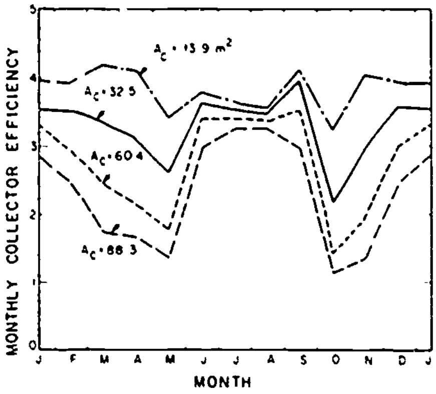


Fig. 3. Monthly Efficiency Versus Month for Several Collector Areas.

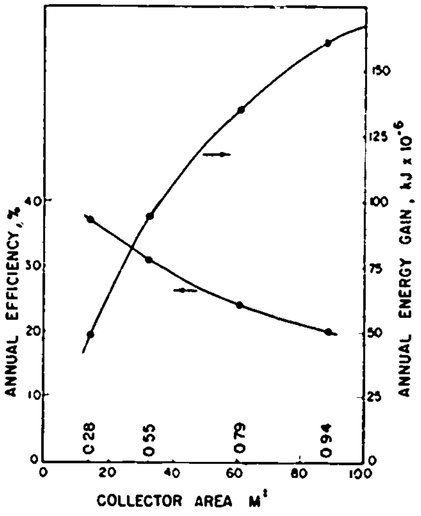


Fig. 4. System Efficiency and Energy Gain as a Function of Collector Area.

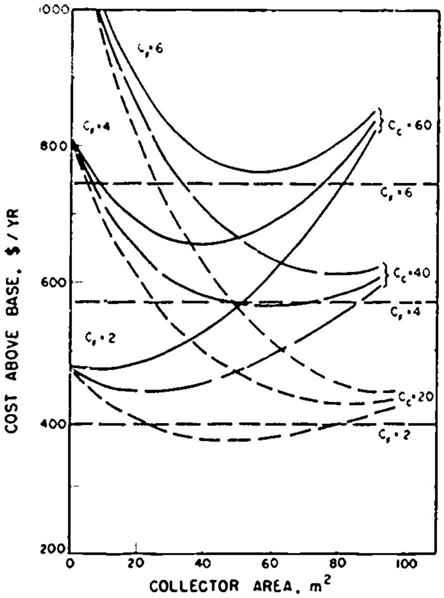


Fig. 5. Cost Comparison and Optimization Plot.

CURRENT LITHIUM BROMIDE HARDWARE AS USED IN SOLAR APPLICATIONS

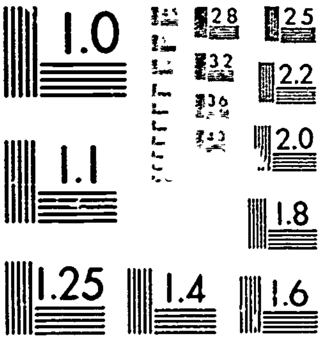
Philip Anderson

Arkla Industries

Arkla has been in the process of changing a direct fired lithium bromide unit over to operation with solar energy. Arkla came into being in 1957 when the Arkansas Lousiana Gas Company purchased the gas air conditioning division of Servel Incorporated. Subsequently, the name was changed to Arkla Industries. Servel was the manufacturer of the gas refrigerator. This unit was a single pressure absorption unit charged with aqua ammonia and hydrogen. Servel extended it to a couple of commercial units with quarter and half ton capacity, and then decided to make an air conditioner. I was a young engineer in those days and I drew the assignment. Dr. Hainsworth, who was vice president of engineering, was later to pronounce it a complete success because the goal was a three ton unit and the unit made two tons capacity and it weighed one ton.

Needless to say, this concentrated attention on other methods. Work proceeded on the salt unit, and one of the first field test units was installed at the World's Fair in New York in 1939. These units were originally charged with a solution of lithium chloride and in order to achieve suitable evaporator temperature it was necessary to operate rather close to the crystalization line. Unfortunately from time to time they wandered over that line. This led to the substitution of lithium bromide for the chloride. These units were water cooled. The absolute pressure on the high side was around one Psia, and on the low side about 0.15 Psia. They used multiple thermosyphon tubes to raise the solution to a point where it would continue its journey through the cycle by gravity; there were no mechanical pumps involved. The units were supplied with their own steam boiler which had a diverter valve that would send steam to the unit or to a heating coil and they became known as All-Year units. In further development, the steam boiler was eliminated and a direct fired unit was manufactured which permitted the use of the same coil for both heating and cooling.

This was the unit which Arkla acquired from Servel. Figure 1 shows a diagram of the direct fired unit. When operating on the cooling cycle, water will be flowing through the absorber, out of the absorber through the condenser, and back to the cooling tower. The burners come on and within a few seconds, the solution in the generator starts boiling and vapor and entrained liquid start passing up the pump tube into the separator head. In the separator head, the baffles separate the liquid from the vapor, the vapor then travels on to the condenser where it is liquified, and flows out of the condenser through a restrictor into the evaporator tubes. Now these are finned evaporator tubes. It is a direct exparsion unit and air flowing over the fins imparts its heat to the evaporator causing the water in the evaporator to vaporize, and the vapor flows down to the absorber. The solution which was carried up to the separator head then flows down a line through a liquid heat exchanger where it is cooled down, back up to the absorber where it is distributed over the tubes of the absorber, and it starts absorbing the vapor. The heat of absorption is carried away by the water passing through the tubes. As the solution flows down through the absorber, it becomes more dilute and eventually it flows out of the absorber, comes back through the heat exchanger where it's warmed up and comes into what we call a



MICROCOPY RESOLUTION TEST CHART

leveling chamber, then flows back to the generator where the cycle is repeated. This is the direct fired unit. We have modified it simply by replacing the direct fired generator with a vessel containing coils through which hot water can be circulated. When cooling is called for, hot water is circulated through the generator coils, and the same process occurs, the solution starts boiling, vapor and liquid pass again up to the separator head and the rest of the cycle is just as it was before.

The direct fired unit of course was equipped also for heating as shown in Figure 2. The temperatures that we have available from the solar energy are not sufficient to activitate this unit for the heating cycle. The specifications for this unit require an input of 55,000 BTU per hour which would be supplied by 11 gallons per minute of 210 degree F water with a 10 degree drop. Now these temperatures are standard specifications with 85 degree cooling water. With 75 degree cooling water, they of course should be approximately 10 degrees lower. Condensing water should be supplied at a minimum of 10 gallons per minute. At 85 degrees, the output of the unit is 36,000 BTU per hour when using 1200 CFM at 80 degrees dry bulb and 67 degrees wet bulb. The dimensions of the unit are approximately 6 feet tall, 4 1/2 feet wide and 2 feet deep. It contains its own blower and filter section. The control section is shown in Figure 3. R is one side of the control transformer and O is the other side of the transformer. On the cooling cycle, the thermostat will connect R with Y which will activate a double pole relay. One pole activates the cooling tower pump and fan. The other pole makes contact between R and A and the connections between O and A go to the pump which supplies hot water to the unit. If for any reason, the evaporator temperature approaches freezing, a low temperature switch opens dropping out the cooling tower relay which cuts off the cooling tower and the supply of heat. In addition if for some reason the cooling tower fails, and the temperature gets too hot, a preventive switch opens to shut off the supply of heat. As the cooling water temperature drops down, it could drop down say from 85°F to 75°F, everything will still operate satisfactorily. But as the temperature goes below 75°F, there is a tendency for the evaporator temperature to get too cold causing the low temperature switch to open. To avoid that when the temperature of the cooling water drops to about 73 degrees a control opens a bypass route, and bypasses a considerable amount of water around the absorber to the condenser, and thus keeps the unit in operation by keeping the evaporator temperature up.

One of the questions that's frequently asked is, "Why did you pick lithium bromide instead of ammonia?" There are several reasons why we picked lithium bromide, but first of all it should be stated that we could use either ammonia or lithium bromide, but in any case with the temperatures that we're talking about to activate the generator, we're going to be using a water cooled unit. We just don't have a high enough temperature for an air cooled unit. We chose lithium bromide because we expect to get a somewhat better coefficient of performance. Also we can use a thermosyphon pump rather than a mechanical pump to take care of the solution circulation. However, if we wanted to put in a mechanical pump, the amount of power required is very little. Another reason is that ammonia is a class two refrigerant and can not be used in a direct expansion evaporator. It would have to be in the form of a water chiller. With the lithium bromide water unit, we have the option of direct expansion or water chiller and we can install the unit either indoors or outdoors.

Another question frequently asked is, "Can't you get the operating temperature of the generator down?" Yes, we can. You must remember that in this case we took our item more or less off the shelf and made a quick modification to operate on solar energy. On a longer development term, we could put in a mechanical pump that would save us some of the temperature difference. The reason is that in a thermosyphon pump we have a certain amount of submergence and at these low pressures, submergence can make quite a difference in the boiling point. At the present time, that's costing us possibly 12 to 14 degrees. If we put on a mechanical pump, we can probably pick up 10 degrees of that. Another way we could pick up temperature would be to increase the amount of surface in the generator. And still another way would be to increase the water flow, split the water flow between the absorber and the condenser instead of using a series flow. Now all of these things of course are adding costs, and you have the question, "Where do you stop?" And right now we've stopped with the unit as you see it.

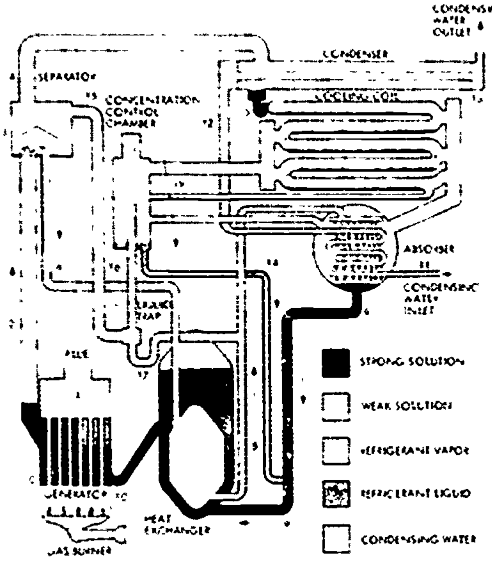


Fig. 1. COOLING SCHEMATIC FLOW DIAGRAM CYCLE SINGLE COIL, DIRECT FIRED UNIT

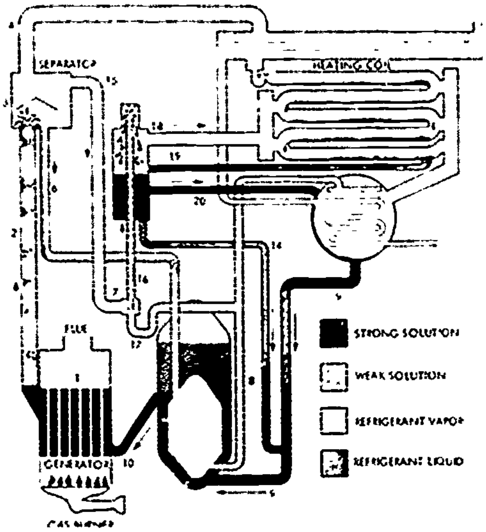


Fig. 2. HEATING SCHEMATIC FLOW DIAGRAM CYCLE SINGLE COIL, DIRECT FIRED UNIT

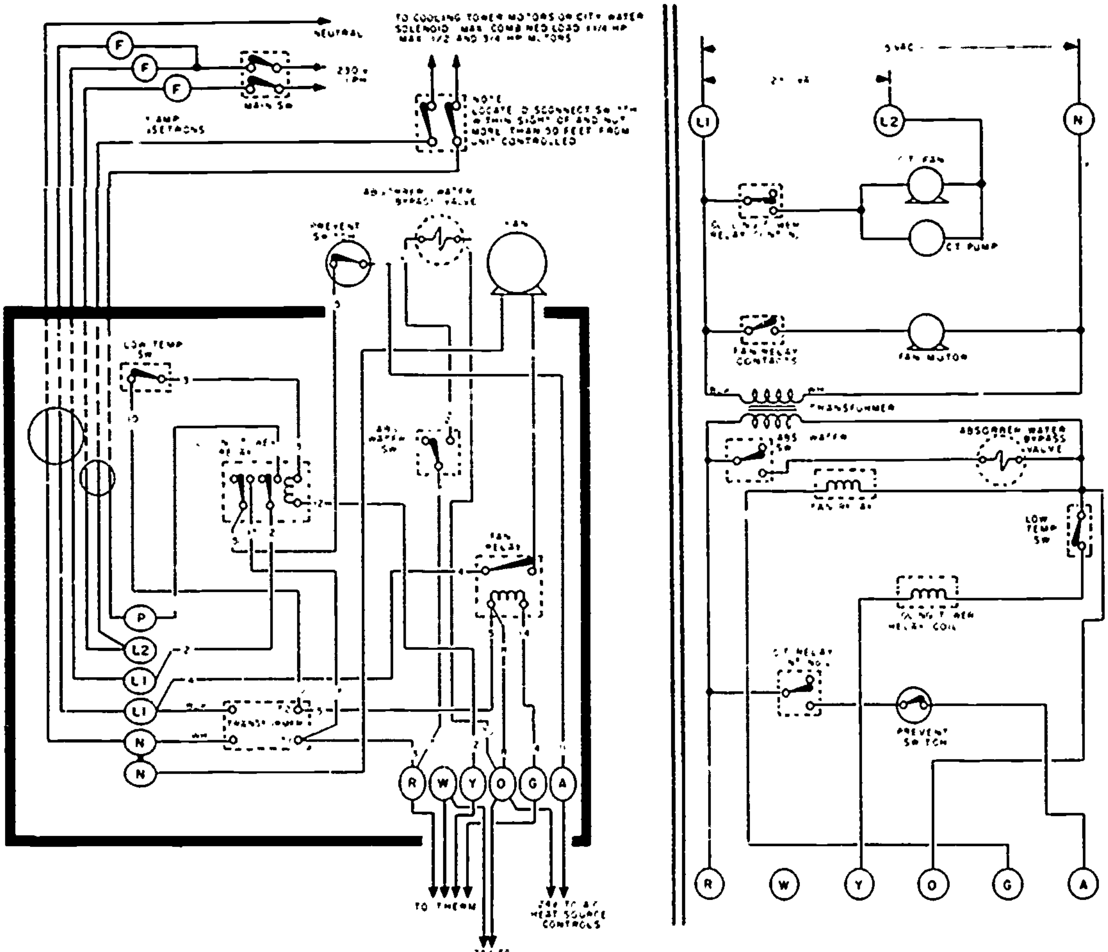


Fig. 3. Control Circuit

A SOLAR HEAT PUMP SYSTEM

James A. Eibling

Battelle-Columbus

I have been asked to describe a concept that we at Battelle have developed on a solar-powered heat pump. We have submitted a proposal on this concept to the NSF. The basic idea was conceived a couple of years ago and stemmed from our extensive experience with rotary-vane refrigeration compressors for several of the leading refrigerator manufacturers. The first application was for the Air Force on high-speed fuel and hydraulic pumps. Later we studied for the A.G.A. its possibilities for a natural-gas-operated air conditioner. The extension of this past research to the application to a solar heat pump occurred in 1973. What we have proposed to NSF is a design study of the heat pump unit itself, leaving the solar collector, the heat storage component, and other auxiliaries to separate studies. Ultimately an entire system would be assembled and evaluated.

Figure 1 is a perspective of one way to embody the heat pump unit into a complete heating and cooling system, in this case a house. The application is amenable equally well to larger buildings requiring up to possibly 100 tons. Here we show a flat-plate collector which outputs into a heat storage tank. Energy for water heating and for year-round heating and cooling is drawn from the storage tank. The heat exchanger transfers heat from the fluid in the storage tank to the heat pump working fluid. The heat pump itself consists of an expander and a compressor and possibly also a motor-generator. The latter, that is the motor-generator, can be used to operate the heat pump on long-term off-solar periods, taking power from the utility grid. At times, especially in the fall or spring, excess power can be fed to the utility grid or used within the building. Obviously, instead of electric power for supplemental use, natural gas or other fuel could supply heat to the expander. An outdoor coil is shown here to serve as a heat sink on cooling operation and as a he ource on heating operation. So now we have a vapor, probably a fluorocarbon, supplying energy to a rotating-vane expander which drives a rotary-vane compressor and the option of electric power or fossil fuel or supplemental energy supply. All rotating components including liquid pumps can be on a single shaft and hermetically sealed.

Figure 2 depicts the system operation on a pressure-enthalpy diagram. Essentially three operating loops describe this system. The top loop in crosshatch represents the path of the working medium as it makes its circuit through the expander system. The middle loop, shows the operation of the compressor on cooling mode. The condenser for the expander and the compressor is the same and the outdoor coil serves that purpose on cooling operation. For comfort heating, the entire non crosshatched portion is representative. Thus for heating, the condenser of the upper loop or expander combines with the condenser of the compressor.

Several variations to the method of operation just described deserve consideration, one being, in extremely cold weather, to use heat from solar energy stored in a second tank at, say, 60 F as a heat source to supplement the heat source derived from outdoor air. Another of course is to use a concentrator collector instead of a flat-plate collector. I'll not take time here for further description of the system as a whole or as to other variations, but rather comment on the expander/compressor unit, which really is the novel part of the concept.

Figure 3 shows one possible arrangement of the expander/compressor. Notice the geometry of the vanes. Instead of ordinary vanes used in the rotary-vane devices, the concept calls for the use of pivoting tips on the vanes. Previous work has shown that a hydrodynamic gas film is self-generated by the pivoting tip, resulting in extremely low coefficients of friction and permitting operation without the use of liquid lubricants. Without lubricants, heat exchangers remain clean and the system can operate to higher initial temperatures. There is also the strong possibility of using a single fluid in both the expander and the compressor. Thus we have promise of development of an efficient machine, mechanically and thermodynamically. When these advantages are added to those of the general class of the rotary-vane machine, that is compactness, simplicity, and low cost, we appear to have an excellent machine for adaptation to solar heating and cooling. Before leaving Figure 3 I should give you a feeling for the size of the unit. We calculate that for a 3-ton machine operating at 3600 rpm on R-22, the rotor is about 4 in. in diameter and the vanes are about 3 in. long. The vane pad is approximately 1/2 inch wide.

Now, if I may go back to the original development work that lead to this idea, Figure 4 is a photograph of a liquid pump developed for the Air Force for pumping JP-4. It operated at 50,000 rpm, at a pressure of 650 psig and 5 gpm flow rate.

Figure 5 shows the application to an aircraft hydraulic pump that operated at 30,000 rpm, 3,000 psig, and 50 gpm. The pivoting tip and vanes are displayed in the foreground.

Figure 6 is a cross-section of the arrangement of the vanes and pivoting tips in gas expanders and compressors.

Figure 7 shows the geometry of a pivoting tip in detail. Naturally, the pivoting tips must be larger for a gas than for a liquid. The various surfaces shown contribute to stability and balance of the pivoting tip as it moves around the cam ring. Not shown are holes through which underblade gas pressure is supplied to insure maintenance of the hydraulic film. We have developed a computer program to assist in designing vanes.

Figure 8 is a photograph of an experimental rig built to evaluate the performance of the pivoting tip when running on gas. The apparatus uses a trunnion-mounted cam ring for measurement of tip drag. The measurement is a very accurate one.

Figure 9 shows the same equipment with the head removed to expose the cam ring in which the pivoting tips travel and into which gas or vapor is introduced and controlled in pressure. Experiments have been run up to 1500 rpm, equivalent to 500 in./sec. with R-12 and nitrogen. The experiments verified the theory of the hydrodynamic film and proved that a hydrodynamic gas film can be developed. The coefficient of friction was on the order of 0.003, which is many times smaller than for vanes that ride on the cam ring. This low tip-friction permits the designer to select geometries that he couldn't otherwise consider.

For a solar-operated heat pump the concept has a number of advantages, as follows:

High Efficiency. High efficiencies of the compressor and expander are essential to gain as high a COP as possible and in turn to minimize the cost of the solar collector and its auxiliaries. With the pivoting-tip vane we should be able to think in terms of adding 5 to 10 percentage points to the adiabatic efficiencies of the compressor and the expander, or a total gain of 11 to 26 percent.

Low Rotational Speed. The vane compressor/expander will operate at either 1800 or 3600 rpm with the motor-generation option or at comparable speeds where the fossil-fuel supplement is used. These low speeds will permit inexpensive bearings and alleviate the need for precise dynamic balancing of the rotating parts. Also the liquid feed pumps can be direct driven from the compressor/expander shaft.

No Lubricant. The pivoting-tip vane is supported on a hydrodynamic gas film without sliding contact so no liquid lubricant is required. With the elimination of lubricants, higher cycle temperatures can be permitted, which improves the overall cycle efficiency. No filters or lubrication pumps are required.

No Valves. The vane compressor and expander can have fixed-port timing with no valves, so flow losses and reliability problems associated with valves can be eliminated.

Low Manufacturing Costs. Combinbing the compressor and expander onto a single shaft reduces the number of parts required for the heat pump --offering the possibility of reducing manufacturing costs. The pivoting tips and the cam ring are relatively simple in shape and appear to be amenable to powdered metal or extrusion fabrication methods. The compressor-expander unit is visualized as being quite compact, requiring low weight of materials.

Adaptable to Wide Range of Capacities. Although the initial application has been thought of in terms of house-sized heat pumps the concept is equally applicable for larger buildings, up to say 100 tons.

We have proposed to NSF that this concept be evaluated as part of the Federal research program on solar applications; the program to begin with a Phase I effort consisting of a feasibility study to complete the analytical investigation of the gas-supported pivoting tip and to conduct critical experiments to verify the analytical results in application to a solar heat pump. Subsequent phases would entail development of the compressor and the expander components and then building and evaluating a complete solar pump system. We at Battelle are enthused about the potential of this concept in the application to solar building heating and cooling.

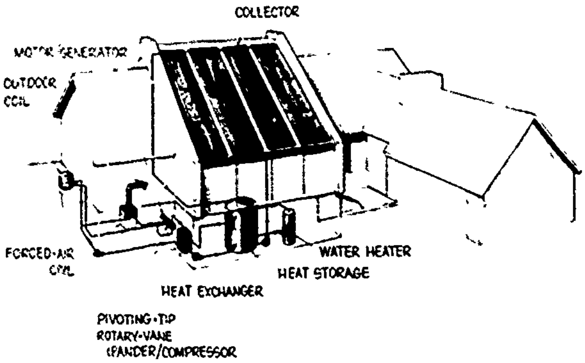


Fig. 1. Solar Heat Pump.

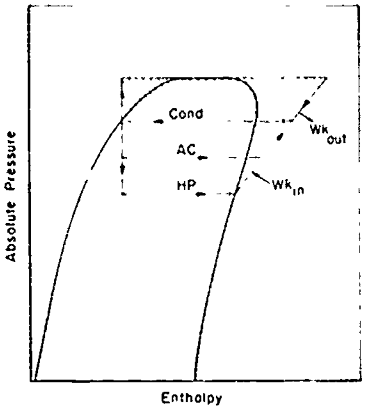


Fig. 2. Pressure Enthalpy Diagram Showing Cycle.

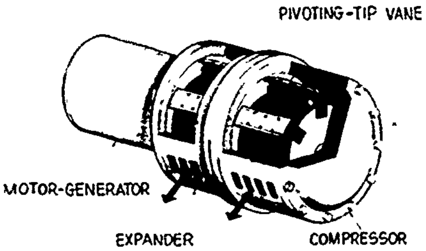


Fig. 3. Solar Heat Pump.

Fig. 4. Liquid JP-4 Pump.

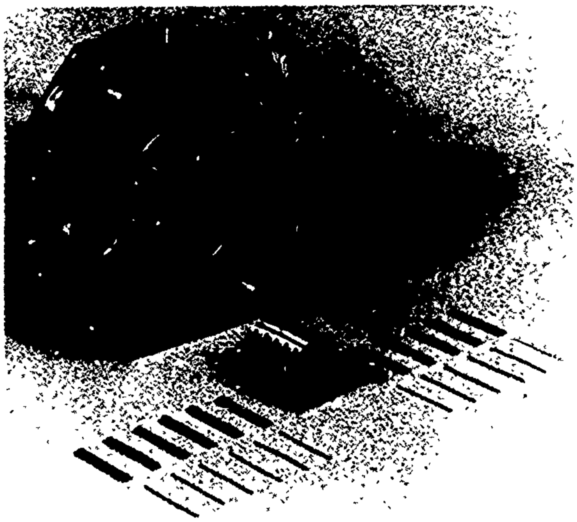


Fig. 5. 30,000 RPM Aircraft Hydraulic Pump.

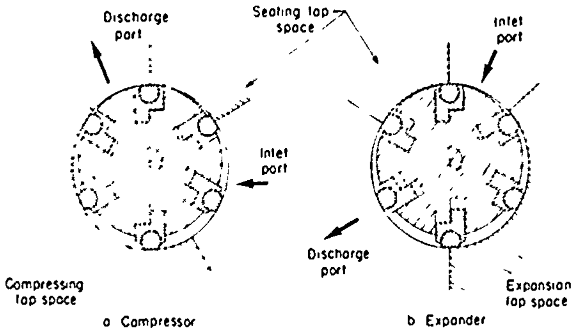


Fig. 6. Cross Section Drawing of Pivoting Vane Pump.

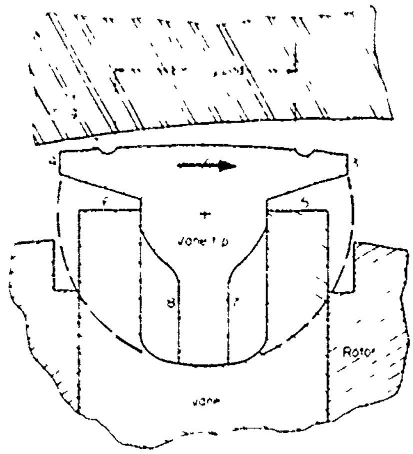


Fig. 7. Detailed Pivoting Tip Geometry.

Fig. 8. Experimental Rig for Gas Tests.

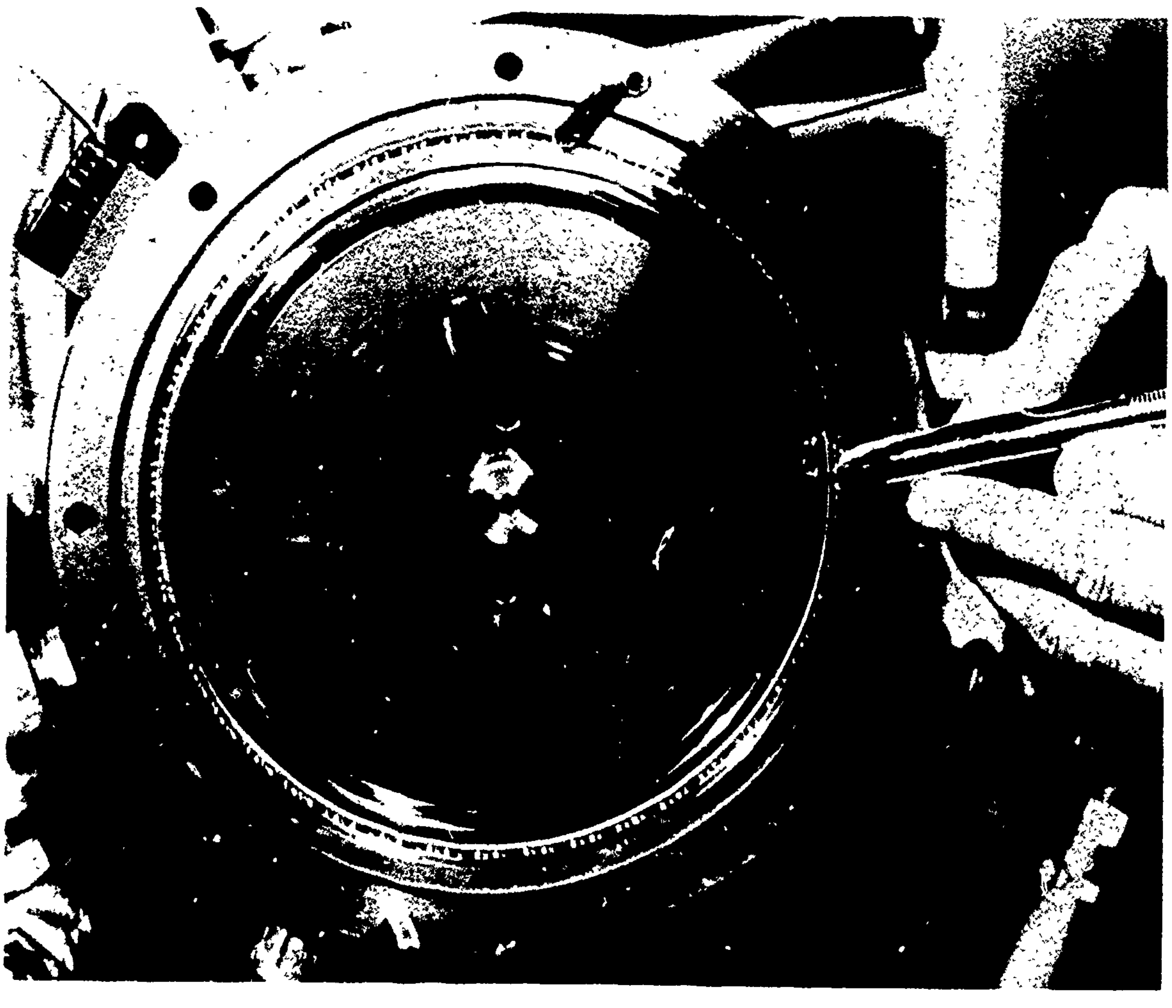


Fig. 9. Gas Rig Equipment Disassembled.

Commentator: Alwin Newton

York

Questions and Answers:

Alwin Newton, York: I think this has been a most interesting session and I think a lot of other people think so judging by the number of questions we've had. I will make just a comment or two first. There were some questions this morning before this session relative to where we are in this solar industry. What is the present status with respect to other comparable things? I'm beginning to think back a little bit when back in the teens warm air systems were quite unusual in houses and there was a great deal of comment and speculation on how to redesign houses to use warm air systems. You know now we have warm air as well as hydraulic systems. The first approaches were simple. They were one pipe furnaces, probably most of you never heard of one pipe furnaces but you used to put one in the middle of the house, and hope they'd heat everything else.

Perhaps in solar work we are a little beyond that stage right now, but we are in the early stages and if we looked ahead, there are going to be a great number of advancements. I have one or two comments myself, which I will try to work in with the other questions. I propose to raise questions for each of the authors in turn. So I'm going to start with George Löf then we'll go on to the next author.

One of the questions that occurred rather frequently was, "What is the material in the "Roll-bond?" The reason for this question is pointed at corrosion problems, and things of this nature.

Löf: We're going to use aluminum roll-bond. This appears to be a reasonable compromise between cost and durability. We are cognizant of possible corrosion problems, so we have a small volume loop containing a few gallons of water and anti-freeze solution. This loop will be protected with inhibitor, one of several types we're looking into. There will be no metallic connections between the aluminum and any other metals in the system. We're hoping to obtain satisfactory service. The alternative is copper which is much more expensive. If the aluminum has adequate durability, it will be a big advantage. Some automobile cooling systems have aluminum radiators and engines so we think similar materials can be used here.

Newton: I think the point on automotive radiators is a good one. It occurred to me on the inhibitors that those used in chilled water systems should be useful to you. There are several questions on the frequency of readings that you take and what's the fine detail you can pick up.

Löf: The instrumentation is designed to scan all the points in the system each five minutes, so there will be a total readout every five minutes. The solar radiation will be integrated over the five minute interval, as well as fuel use, electric use, and water supply. All the other readings will be instantaneous readings.

Newton: A number of people would like to know what the pressure drops are and how much they contribute to needed power from fans, pumps and things of this nature. Do you have a hold on that you can give us at this present time?

Löf: I'd like to call on Dan Ward for that. Dan Ward is the project manager. If you don't have those numbers in mind we'll supply them later.

Newton: Then the question was asked by a number of people,-"Are you really convinced that you need the two fluid system?" Isn't it practical to drain the collector and therefore avoid one temperature difference at least in the system, drain it whenever you're in danger of freezing?

Löf: We're not convinced that we have to use the two loops, but we're providing them as a precaution. If we find that the solar collector can be self draining on a fail-safe basis, we will dispense with the heat exchanger and the separate loop. The plan view of the solar collector shows all the tubing is sloped; even the manifolds have a slight slope. If we find that we don't get air binding, and that drainage is complete we'll not use the heat exchanger. But unfortunately, nearly every collector that's been constructed using a water system in a cold climate has at some time or other been damaged by freezing. This is an expensive accident, so we're going to avoid it one way or another.

Newton: Along the same line, do you have any feelings in the difference of COP that you might have in a cooling cycle working off a direct interchange compared to working off the storage?

Löf: The COP from heat to cooling would not be affected because the COP is relatively constant from 180 degree supply to a 200 degree supply. However, the COP from solar to cooling would be improved by dispensing with the heat exchanger. We could get about a 15 degree temperature advantage if we don't have to use the exchanger. This would permit the solar collector to operate more efficiently. I would estimate that this probably would permit a reduction in collector size of perhaps 10% to 15%. However, the system must also provide heating, and heating is more demanding in our Colorado area than the cooling is. Bill Beckman reminds me that a one degree change in heat recovery temperature is accompanied by about one percent change in system efficiency. So 15 degrees is equivalent to 15 percent.

Newton: The question has been asked me by three people as to why glass is used to cover the collectors instead of some form of plastic. Several people commented they thought by now plastics might be available.

Löf: The main reason we are using glass is that from our own experience we know it's dependable, servicable, and an excellent construction material. There are windows around here over 100 years old. There are no plastics that have the life that glass has. Also, it has high solar transmission. If you're going to use rigid plastic with as high transmission as glass, higher costs will be encountered. Some types of fiberglass reinforced polyester have solar transmission a little higher than glass, and they might be useful as a top glazing, where their maximum service temperature would not be exceeded. Plastic films degrade, due to UV absorption, and I do not know of any types suitable for long term use. Inside the unit, you have to provide for a fail-safe temperature of somewhere around 400 degrees F. which is well beyond the range of all but the costliest plastics.

Newton: One last question, Whether or not it is easy to test other materials. One question suggested that a selective surface material might be provided for testing, is it something you could work into your collection system?

Löf: One of the purposes of this installation is to serve as a test bed for other collector designs and materials. We would not be able to incorporate this change in the installation now. But after this system has been tested for a year, and we have the data on it, we expect to install other systems and materials. We would then like to evaluate selective surfaces as well as other materials.

Newton: I'm covering all the questions we received of course, and later on I understand there will be a chance for audience questioning.

Bill Beckman will come next. While you're on the way, I'd like to point out that quite a number of people, I think I can include myself on this, were a little bit confused by the term "efficiency" as you used it and wondered if since this seems to be related to the amount of time during which you can use all of the energy from the collector, are we not really talking about a utilization factor in terms of they way a utility would look at. Would you like to comment on that.

Beckman: The term "efficiency" as I use it was the ratio of useful energy gain leaving the collector that gets to the storage tank divided by the solar energy incident on the collector. It doesn't include losses from the storage tank. It's really a collector efficiency.

Newton: Well fine, I think as the curve showed some of us thought that it might mean you had more solar energy available than you could use. That factor is included, which does border on the utilization factor I guess. It comes from the combination of the actual efficiency of conversion of solar energy to heat at the collector plus the amount you can use.

Beckman: The point was that you can not really look at a collector by itself, you would have to put it into the system. When you put it into the system it behaves in strange ways and some of the useful energy gain that you could get out of the collector the system just won't accept. So in a sense it's a collector efficiency when coupled with that particular system.

Newton: I think that will answer everybody's question. Another question. How much computer time is needed for example, to analyze a year on a system? Now you may prefer to answer this a little bit differently, but that's the way the question was posed in two or three cases.

Beckman: I guess it's dollars that are more important and here again it's difficult to assess costs in one computer compared to another. On our particular computer. It turns out to be about $10 per month for each design. So that would be on the order of $120 per year. Recently we arbitrarily have decided that's too much and we generally look at only two weeks out of each month assuming that the first two weeks look like the rest. We've cut our costs in half by just looking at two weeks. Future developments will significantly reduce that cost.

Newton: Since you didn't state in it that answer, I'll ask this next question. What is the computer you use?

Beckman: At Wisconsin, we have two machines, a very large one, a Univac 1110 and what's called a mini computer, a Datacraft, I'm not sure of the number. Most of our work is done on the Datacraft. The Datacraft is extremely fast and we avoid the large machine at all times. We only go to the large machine when we have to.

Newton: Can your programming relate the amount of collector surface I assume in square feet, to the amount of auxiliary power needed? Is this a capability of the program?

Beckman: Yes, that comes out automatically.

Newton: I guess the last question we gathered for you is whether you can identify a relatively small range which seems to be the best optimum point for the addition of auxiliary heat. I don't know if this can be done for systems in general or whether you would have to refer to a couple of specific systems.

Beckman: Our experience on a number of specific systems indicates that at the optimum 60 or 75 of the total load might be carried by solar. One just cannot conceive of an economic system at the 95% range.

Newton: All right I think for the general questions that leaves you off the hook, and we'll go to Phil Anderson next. I had several people who asked, Why wasn't anything said about two stage or dual effect absorption systems? Since you're the absorption expert, maybe you'd like to take that one.

Anderson: The temperature limit is the reason the double effect was not mentioned. The double effect unit of course is more efficient, it has a high coefficient of performance, but it also has a much higher operating temperature.

Newton: Input temperature yes. A number of people have asked the question as to why the COP seems to be fairly constant over wide range of input temperatures like 180 to 220 degrees F? Right along with that I guess there are questions, does the capacity of the same system change when you drop the temperature through some such range, 200 to 180 for example?

Anderson: That depends on the conditions. For example, the one that I cited at 210 degrees and 35 degree condensing water gives full capacity. At 85 degree condensing water, if you drop that temperature down say to 204, you're getting about 80% of the capacity.

Newton: And was there very little change in COP?

Anderson: That's right.

Newton: Does the COP figure that you mentioned include any allowance for accessory equipment?

Anderson: No it does not. This is based on input to the unit.

Newton: Then I guess a final question, is to give us some idea of the total amount of water as well as the temperature rise that's needed. I believe you mentioned a 10 degree F rise in the cooling water.

Anderson: A minimum of 10 GPM of the cooling water.

Newton: And what is the temperature rise?

Anderson: About 18 degrees.

Newton: Now we come to Jim Eibling. Everybody wants to know what is the compressor efficiency and the expander efficiency separately. Now I suppose this is referring to thermodynamic efficiency, however you want to answer it is all right.

ANSWER: Well, as I mentioned, we think in terms of five to ten percentage points higher with our machine on paper than the standard rotary vane machine. Translating that range into an isentropic efficiency, a conventional rotary vane machine will go 75%. If we add 5 to 10 points to that, we're talking 80 to 85 for the expander and the same range of values for the compressor. So on an overall basis, we are estimating somewhere in the range of 64 to 72 percent isentropic efficiency for the entire expander compressor unit.

Newton: Another question related to how this whole system, the expander and the compressor respond to changing mode conditions and in addition to that how do they respond to different input temperatures? Is there some pattern that is better with some systems and how do they relate?

Eibling: We haven't thought through that question all the way, but we look at it like any vapor engine or rotary-vane expander in other applications. Our machine has a reasonable "turn-down ratio," I guess is the term. If we change the load appreciably and change the speed also, we'd have some surface contact problems except that we compensate for this by underblade gas pressure, introduced between the blade tip and cam ring. We believe we can vary the speed and load quite a bit just as you would throttle a steam engine.

Newton: Can you give us any information on the materials in the pivoting vanes? Are they critical and likewise in the cylinder?

Eibling: They're critical. First of all from the centrifugal force point of view, we would like the tip to be light in weight. Carbon graphite works out fine here and the vane itself, into which the pivoting tip is inserted, could be aluminum. Bear in mind that there is gas pressure underneath that aluminum blade, too. The chief concern on materials is on startup when you have contact of the tip on the cam ring because the tip velocity is not yet up to the point of establishing a hydrodynamic film. So materials have to be compatible for this occasional contact. One solution is carbon graphite with a special surface coating and a coated stainless steel cam ring.

Newton: Well there is another one right along the same line. Most rotary compressors must have a close control of leakage at the contact point with the rotor, and how is this done without lubrication?

Eibling: In one of the diagrams of the pivoting-tip machine you saw a complicated shape. All those surfaces have meaning. The experiments we have run so far show that we get very good sealing at the trail edge of the hydrodynamic wedge. The question was well put because the traditional rotary-vane machine relies on oil for sealing and cooling as much as it does for lubrication. Since we've taken that oil away we have to substitute other means of sealing. We think the pivoting tip takes care of that.

Newton: There are questions about the electric power generation from your solar system. Is it true that you are connected to the electric grid for putting power back into some utilities system? Also, can you give some possible input to how much power this system might supply to the house itself?

Eibling: You could tie in with the utility grid. This is optional. Unlike the photovoltaic cell that generates DC, we can generate AC having characteristics of power compatible with the utility grid. Of course we've got to have close control of frequency and voltage and there are ways to do that over a wide speed range with field modulation. There are times in the solar cycle when no heating or cooling is required, i.e., spring and fall, and there is very high solar insolation. It is inviting at these times to make electricity. Hopefully by building a motor/generator combination, we can either drive the unit with electric power or feed power back into the grid. At this point I don't know how much power might be available.

Newton: Total to the house is what we're talking about too.

Eibling: Well, another option is, instead of connecting with the utility grid, to use what power you can generate in your own household using some reasonable amount of energy storage.

Newton: I guess the last specific question to you deals with what's the lowest temperature at which you believe this system could operate and I don't know whether this means at full load or part load but you could perhaps comment both ways if you want to.

Eibling: I don't yet know the answer to that. Engineers want to operate at the highest temperature possible for maximum efficiency. I'd like to see 180 to 200 degrees F minimum initial temperature, which of course is obtainable with a flat plate collector. If we go to higher temperatures, toward 300 or 400 degrees F, where we will have to use a concentrator of some sort, and we may lost the advantage of a single fluid, i.e., if the expander operates at a much higher temperature than the compressor, we may have to use two different fluids. So there is a tradeoff here. But initially we would like to look at the flat plate as one case study, and then look at 400 or 500 degree F initial temperature as a second case study.

Newton: I think I'll make one comment myself on this temperature question, with this type of system and the fact that we're using a fluoro carbon type material. Quite a bit of work has been done to identify the top temperatures that you can use, and as soon as you get up in the 400, 500 degree range, you're probably limited to just two or three materials as we know today, unless you want to spend maybe $30 or $40 a pound. The most promising material of all as far as I know would be R114, and a great deal of work has been done with R114 at temperatures of up to 500 or 600 degrees. You have a big advantage here in not having oil in the system. It won't tolerate those temperatures with oil, so these are just some side comments that we could have. Now I guess the next step is to open up with some general questions.

Lokmanhekim, Hittman Corporation: I have a question to Professors Löf and Beckman: They mentioned in their presentation that they use eight cities for models. To my knowledge there are several stations in the United States that have been data recorded and there are limited amounts of solar radiation recorded, and much of the data are not consistent. So since this is the case, the question is: How they build up their solar radiation data in their simulation model? What kind of equation they use for the direct component of radiation and the diffuse component of the radiation? In the diffuse component of the radiation did they consider radiation from the ground and radiation from the sky?

The second question is actually a comment. Professor Löf mentioned that "What matches supply?" I think we have to clarify this statement. As you ASHRAE members are familiar with the 1970 guide and data book, there are three terms in the ASHRAE energy requirement. One is heat gain heat loss, the other is cooling or heating load and the other term introduced heat reaction or heat supply rate. I agree with the statement that you make, heat gain or heat loss match with the supply however, it never matches with the loss because we have to consider the dynamic response of the building, heat storage effect of the air inside the building, heat storage effect of the furniture, heat storage effect of the floor, etc. So we have to analyze this thing because I don't think there is a building which has a maximum cooling load at 12 months, which is your heat gain maximum. As most of you know that ASHRAE Task Group on Energy Requirements built up digital computer models to simulate the building heating and cooling energy requirements. In IBM computers like the 370-155 our load calculation and system simulation does not exceed in the order of $50 per year, for an hour by hour simulation. I was wondering why the Beckman figure of $10 a month is so high. Another suggestion is the people from Wisconsin might consider just using few hour of each month to predict what happens. In other words, linear type solutions. And also, we have to really consider definitely the change of the room temperature. Because of the dynamic effect of the control system the room temperature might be anywhere between 69 1/2 and 74 degrees. So are these things considered in their model?

Löf: I agree on the comments on the thermal lag and the dynamic effects of the masses in the house. Our model was a very primitive model and did not include these at all. Bill Beckman was very generous in his comments in not pointing this out. Really it is a primitive model and doesn't include that. It's a very important point. As far as the first question, the diffuse, radiation is concerned, a regression equation was developed by my coauthor Dick Tibout on the basis of some diffuse radiation data in four cities and the total radiation was split into direct and diffuse by use of this regression equation. Then the diffuse radiation was assumed to come from an entire hemisphere so in effect the effect of the surroundings was assumed to be 100%. It's crude, but it turns out that with the amount of diffuse, you can be pretty sloppy with this and still come up with what appears to be pretty good answers and I think Bill has a comment on that point.

Beckman: A comment on how we handle the diffuse. Our assumption was that when diffuse is a large fraction of the total energy, the total amount of energy is usually small. Our assumption was that all diffuse comes from the vicinity of the sun and the error involved, as George points out, is reasonably small. That is a different assumption than George made. People have argued these two points for many years, and I don't think there is really a definitive answer on how you should handle it. As far as computer costs are concerned. We developed a model that tried to simulate the dynamics, not just on an hour by hour basis, but on a quarter hour, or eighth hour, or whatever was necessary in order to maintain an integration accuracy below some value. The program automatically looked at half hour steps if it was necessary, or quarter hour, or eighth hour. We had to linearly interpolate the hour by hour solar radiation values because some of the equations are unstable if you look at time periods on the order of an hour. When you do 8,000 hour by hour calculations, maybe we really did four times that many quarter hour calculations.

It's ridiculous to do the same house model over and over again when you're just varying the collector area. The house maintains a roughly uniform temperature, and all the loads on the house in that same climate are roughly the same. So we're going to run the house once and then couple it with different solar energy systems, and significantly reduce the cost to a few dollars for a year. It would still include the dynamics of the building and control system.

Harry Buchberg, UCLA: It wasn't clear to me, George on your diagram just how you handle the auxiliary heater in the cooling mode. It appeared to me that you were not actually boosting the temperature from the main supply tank and if not, I would like to comment on why not.

Löf: Your interpretation is right. We use either the heat from storage or heat from the auxiliary heater, but never both at the same time in the cooling mode. The reason for this is that if we try to boost the storage fluid temperature by means of the auxiliary unit, we get into a situation such as Bill Beckman mentioned; we're supplying heat from the auxiliary unit to storage. This is undesirable because this fuel heat would occupy useful storage volume and secondly, collector temperature would increase and efficiency decrease unnecessarily.

John Boretz, TRW: One question is how critical is the over temperature problem associated with the solar collector in the event of the loss of circulating fluid? Will this increase the possibility of damage or greatly increase the cost to build the solar collector to take into account a possibility of a 300 to 400 degree temperature due to loss of the operating fluid during the day, let's say on a hot cooling day. The second question I have is that we haven't discussed at this workshop at all the possibilities inherent in cold storage and I was wondering why that hasn't been discussed, and thirdly, the potential associated with the regeneratively heating of the fresh air supply to a house that might have to have up to maybe 30% fresh air supply hasn't been discussed here either.

Löf: As to the danger of over heating, we are not going to use any material in the collector that won't withstand 400^{0}F because of the problem you mentioned. I think any collector has to be fail-safe. Even during construction, it can seriously overheat unless covered. I shall refer your second question to my colleague, Paul Wilbur, who has looked into the storage of chilled product from the air conditioner. In answer to your third question on fresh air makeup, we're going to have about one air change per hour in the house. Regenerative heating of this air would be a heat conserving measure which could be considered, but we have not done so. We are using our "ground rule" that this house should be typical of today's design.

Paul Wilbur: We're involved presently with the Westinghouse part of the three company program in evaluating solar heating and cooling systems. The idea that we have been examining or one of the ideas includes generating refrigerant during peak solar heating hours, storing that refrigerant until it's needed, then transferring heat from what is usually used to store hot water in the winter months. We're actually cooling that down to the cooling tower or a possibly an air heat exchanger so that we have cold water system for transferring the heat from the absorption unit. The difficulties with this may involve control, they may involve the costs of the lithium bromide solution that has to be stored in the system. We're presently doing a dynamic simulation to determine whether or not this is a viable alternative.

Newton: I think I can make a comment myself. I've had a question or two about some of the early work I did in the early 1930's on storing cold and this dealt with night radiation, sky radiation at night. I think it's something we ought not to forget, but one of the problems is the difficulty of having a collector which can both receive sun radiation and prevent reradiation and then at the same time, radiate at night. You're defeating yourself and the work at that time indicated that you needed two collection systems. Maybe sometime we can find a way of handling that with only one.

Harold Horowitz: Yes, I'd like to respond to one of these questions because it's a general question that I've been receiving yesterday and also this morning. People have been coming to me and saying, "Why don't you give us a chance to talk about some new collector ideas?" Perhaps some collector ideas that will give us higher temperatures and I've been telling them no, and people this morning have been coming, several, and have wanted to talk about other kinds of approaches to this problem which don't use this solar collector. I said no to some of them and I'm saying no to the others that I haven't said no to now. Also the reason why we're not including storage in this workshop, is the same kind of question, and I'm saying no to that except as it might come out in one of the system studies which is related to the cooling subsystems which is the objective and central purpose of this workshop.

I am trying to go from the very general broad scope workshop which we had last March, to the workshop that we're having today, and hope that more workshops that we hope to have will now be concentrating on these special areas because we're beginning to find that we have enough material to make that kind of concentration possible. And of course it irritates people who want to talk about the related subject matter, and I can understand that but the reason for not bringing in the related subject matter is because you're going to be up until 11:30 tonight listening to presentations on cooling and we won't be finished until tomorrow lunchtime, with presentations on cooling. We have just that much to say about cooling and we just don't want to stretch this meeting out over the weekend, because that would probably make you just as unhappy as leaving out the collectors and the alternative approaches and the storage components. Yesterday, when we discussed our general plans we mentioned that we're thinking now of having the next workshop sometime later this year, where we would try to cover some of the new work in collectors and some of the new work in storage systems. I hope you all come. There are some interesting things to say in those fields. We're making progress in those areas. In some respects with collectors, we're further ahead than we are with cooling and further ahead than with storage. But we're trying to make some progress along the whole front. In the area of the non collector solar approaches so far, we have made only one grant out of this program. It's Timothy Johnson at MIT and he's studying variable membranes which can be controlled to selectively transmit solar radiation into the building or reflect it. The concept there is that the whole building is the collector and by the proper choice of membranes and by manipulating them, you can reradiate radiant energy generated within the structure. Reflect radiant energy impinging on the structure and transmit radiant energy into the structure. Now the obvious allocation for that is the inflatable structure which we're seeing more of in the United States, but also the possibility of putting such variable membranes into frames which could become part of a roof or wall. Now, that project is just getting started. We understand that the progress so far is better than was anticipated in the proposal. One of these days, we're going to create an opportunity for them to tell you about it.

We have another proposal that is generally related to that area which is now in the final end of the processing pipeline at NSF, and I hope an award will be made very soon. If you recall the November 1973 program solicitation had a category B, which invited proposals of this sort, we were very surprised with some of the ideas presented. There were some great ideas presented under that category, and as a matter of fact, the evaluation panel for that category came as close as any that I can recall in unanimously agreeing that one was the best and standing up and cheering because they were so happy with it, and they estimated that if it turns out to be as good as the proposal locks, it could revolutionize the whole construction of buildings. Well, I don't know if that's true or not, but we hope to be funding that project in the next couple of months, perhaps one or two more in that category and so sometime, perhaps this coming fall that may be a little optimistic, perhaps next spring, we'll be trying another workshop in that area to give exposure to those projects plus new ideas along that line and that's the reason I'm saying no to you who would like to broaden this workshop to include these other subjects.

Dave Sutton: The question has come up a number of times on the size of the heat transfer surface areas. Phil Anderson in his discussion gave us an idea of the overall size of the absorption air conditioning package which I believe Phil said also includes the evaporator heat transfer coil. Might you comment on the size of that coil as contrasted to the one used in the typical vapor compression system and also on the size of the cooling tower.

Anderson: I would say that the evaporator used in the unit itself for cooling is somewhat larger than normally used in the vapor compression machine. Remember, we're handling vapor at very low pressures. The specific volume of the vapor is quite high there, so we have to have larger tubes. For example, the tube diameter outside is 1 1/8 as compared with what you normally have in the vapor compression cycle. So this evaporator is larger. Now on the heat rejection, you recall that in the compression machine you reject your heat in the condenser. In the absorption machine you reject your heat in the condenser and in the absorber. So essentially, you're rejecting heat twice, so therefore you would have to have a larger tower. It doesn't follow that you have to have a tower twice as large because instead of rejecting heat at let's say 90 degrees, we're going up to about 105 degrees, so the size of the tower would not be double the tonnage.

Anonymous question: I would like to ask maybe Löf or Anderson some questions along the same line which relate to the conditions under which some of the components are working. Specifically in the system Lof is now putting together which is now under construction, at what temperature does the lithium bromide boiler actually work and then for Anderson, what is the output relative to the full load design point in the sense you indicated before? A second question for Löf, what is the temperature output of a solar panel and where are the temperature drops along the processes as you go from the panel to the lithium bromide boiler? Then if I could ask one last question, what is the adjusted efficiency of the solar panel in the sense that Beck commented on and how does it compare to a nonadjusted efficiency. I know these are not single points, the system does not operate at one single point, but you know, if we had information of this type, it could help us to just take one glance at one point or typical point and see just what these pieces of equipment are doing from an effectiveness viewpoint.

Löf: The temperature of the heat exchange fluid, nominally delivered from the collector will be around 200 degrees F in the summertime. This will vary from 180 to 210 depending on conditions. The circulating pump is operated by means of sensors in the collector and in the storage. We run it when heat can be delivered to storage at about a 15 degree difference. If the collector delivery temperature is 180 to 210 in the summertime, the temperature difference in the heat exchanger would be about 10 to 15 degrees to water in storage. The water storage temperature is limited to a maximum of 202, which is the boiling point. The supply to the lithium bromide unit will normally range from 170 to 195. The overall seasonal collector efficiency on the basis Beckman discussed should be about 30%.

Anderson: I'd like to ask once again, what is the specific question on the temperature?

Question: If the temperature to boiler stays 180 degrees, say one of the lowest temperatures, what is the output of the unit in relation to its design point full load?

Anderson: Let's come back to the conditions I quoted originally, that was for 210 degree water in. The generator temperature at that time would be probably 186 degrees and that would be full load. Now as you drop down say the cutoff point for 85 degree water would be probably about 192 to 194 where you're getting 60% of your input. Your generator temperature would drop down accordingly. Does that answer your question? Now you're putting about 60% input in and you're getting about 60% output.

Löf: There might be a little confusion here because we're operating at a cooling water temperature of 75°F and I believe the numbers Phil Anderson is talking about apply to operating with cooling water at 85°F. The lower temperature permits operation with generator temperatures down about 10 degrees. Is that right?

Anderson: That's right. I intended to make that point but I got to talking about the other temperatures, and forgot to mention that they are operating with the 75 degree water which of course, lowers that point.

Löf: I'd like to ask a question of Jim Eibling. How do you deal with speed variations of the unit when electric networks operate at constant frequency?

Jim Eibling: We could put a speed controller on this device and keep a constant speed, but I'm told by electrical engineers, there are devices that will take care of your voltage and frequency with variable speeds, quite a wide range of speed, in fact.

Charles Grant, University of Southern Mississippi: I'd like to ask Löf, what are the initial costs on this 1500 square feet house of a production line installation, are they in the neighborhood of $6,000, $12,000 or what?

Löf: There are a number of answers to that question. I think we have something like $10,000 in our construction budget for the entire system, including the air conditioning unit. I can give you a few items of cost, but I can't tell you what the total will be, because I don't know what our labor costs are going to be. The solar absorber panels are going to cost us 67¢ per square foot, the glass is going to cost about 35¢ a square foot per sheet and we're going to use two sheets, insulation 10 to 15c a square foot, and support hardware about 25¢. So the cost of materials will be $1.50 to $2.00 per square foot of collector. I don't know what the labor of assembly is going to cost, but it's going to be substantial. The collector is going to be built up on the house. Assembly of components, cost of the storage tank, the control system, and other items must then be estimated. I would estimate, that on sizable production volume, which I believe the questioner indicated, the total cost with the air conditioner would be something like $5,000. Without the air conditioner, I would guess about $3,000. That's about as well as I can do until we obtain more data.

Charles Chen: Those of you who have not had a chance to ask questions, we're going to continue this afternoon on the same topic. I would like to thank our morning speakers for their enthusiastic participation. The meeting is adjourned.

PLEASE NOTE: Questions and answers on this session are carried over into the Question and Answer part of Session III.

SESSION III - ABSORPTION AND HEAT PUMP SYSTEMS

Session Chairman: Charles Chen

AMMONIA AND OTHER ABSORPTION SYSTEMS USED IN SOLAR APPLICATIONS

Erich Farber

University of Florida

First of all I might mention why I became interested in solar energy. When I was in high school and studied history, it occurred to me that the growth of civilization and its development was directly proportional to the amount of energy they had and used. When I looked where this energy had come from, namely the fossil fuels, it looked like a savings account. As we draw on it, sooner or later it will be used up. Everyone agrees with this but not everyone agrees to when this will happen.

Looking around as to what else we could use when the fossil fuels run out, the only energy source large enough and permanent enough which I could find, and which could be classified as income, was solar energy. Therefore, my philosophy since then has been to show that we can convert this source, our only energy income, to all the forms of energy which we use in our daily lives. We have so many different devices in our laboratory because we are trying to show (whether it is economically competitive at the present time or not) that we can actually use solar energy for everything we do.

I feel we will always have to use all our energy resources fossil fuels, nuclear, wind, geothermal and naturally solar, etc. Fossil fuels should be reserved as much as possible for medicines, fertilizers, pesticides, preservations, plastics, etc. which are just as important to our survival as energy. Nuclear energy has potential hazards in riots, sabotage and wars.

We are discussing solar cooling, however, I observed that very few participants restricted themselves to this, and I shall do the same since I do not believe you can consider one thing by itself and isolate it from all other things which affect it. We have to look at the over-all picture, economics was mentioned many times, since if we consider solar cooling by itself it is definitely not competitive at the present time. If we combine it however, with heating, hot water and swimming pool heating the picture changes. One good example was Dr. Löf's slide this morning. I wish he would have shown the one he had a year ago where he considered only heating. It showed that solar heating in Miami, comparing the same towns, was about the worst place to use it. Today, when combining heating and cooling, it showed that Miami was the best place to use it.

Our support from the National Science Foundation is to develop a data base from the things we have done, plus new things for solar cooling. In doing so we have to make a thorough literature survey. We developed tables of solar insolation, which were mentioned several times already by others, because when working with a source it is important to know how much of it is available. This saves the necessity of having to make all the calculations every time. We looked at refrigerant and absorber combinations and found, as we found 20 years ago, that there exists a tremendous lack of information. There are thousands of combinations possible, but there is not enough data to really analyze these combinations. So eventually one use ammonia and water or LiBr and water.

There are other combinations and they look promising but more data has to be developed. In talking to some of the people from industry, they have combinations of organic substances that they eliminated in the past, because in the temperature ranges they worked with, these combinations decompose. In the temperature ranges, however, in which we work, they may be very good. Unfortunately, much of this information is proprietary and therefore not readily available. However, as I understand it, some of the companies are trying to obtain support from the National Science Foundation which I hope will allow to study these combinations.

In looking at these combinations, we have to consider absorption rates, heats of solution, concentrations, heat transfer characteristics, water cooling versus air cooling, etc. With air cooling more non-solar energy is needed to power the system. With water cooling, water has to be available but could be recycled. In most cases this would not be a problem since more than half of the total tonnage of air conditioning is water cooled. True, in small units at the present time because of the low cost of electricity air cooled units outnumber the water cooled ones. With the rapid increase in electricity cost however re-evaluations are being conducted. Cycle analyses with these various combinations are necessary to determine what actually goes on in every part of the system.

Many people feel that we have to use presently available commercial equipment and just change it slightly to fit the new conditions. Much work went into the design of these systems to optimize them for the conditions under which they were supposed to operate. With solar energy, we may have to fit equipment to different operating conditions, and it should not be more difficult than it was to meet the old conditions. It is much more difficult to take equipment designed for certain conditions and make it work at different ones - even if modified.

In doing this work we have help from many other people, I like to especially mention Dr. Phillips, who has for many years been with Servel in absorption air conditioning and then with Whirlpool and now has his own company continuing the same type of work. We also have the support of a marketing company with Mr. Parker, vice president of Miller and Associates.

To show you what we are doing, I'd like to show some slides. I use Figure 1 as introduction. For thousands of years until very recently we lived off solar energy alone. Even fossil fuels are nothing but stored solar energy and we are using it even now. We are probably doing the very unusual in the Universe since solar type of energy is very abundant throughout space but not in many places does one burn coal, oil or gas. We have only a spike and that is all that fossil fuels can provide. Therefore, we have to stretch and conserve our fossil fuels as much as we can.

We should build buildings to conserve energy and certainly we do not do this today. We did before air conditioning became popular and we built buildings so that people were comfortable. With air conditioning we could build buildings any way we wanted to. Some are essentially a glass box, collecting solar energy and then by brute force, burning fossil fuels, that energy is thrown back out again. The other extreme are buildings without windows. You need lighting, and lighting is very inefficient, producing tremendous amounts of heat, and as a result you have to leave the air conditioning running all year around to keep the building comfortable. Neither design makes much sense.

As far as air conditioning is concerned, obviously we can use conventional methods. All we need is some mechanical work to operate a compressor and do the standard air conditioning or refrigeration job. Figure 2 shows a Stirling engine. The solarly operated Stirling engine in this particular case pumps water, it could drive a generator and produce electricity or it could drive an air conditioner, or refrigerator. This method requires solar concentration.

Unfortunately, one can only use the direct radiation in this manner, and could not do anything with such a system on a cloudy day. Besides a tracking mechanism is required and this complicates the system and makes it more expensive and less convenient. One can do the same thing with flat plate collectors, taking a proper fluid, which at the flat plate collector temperature produces vapor which operates a vapor engine, flows then to the condenser, and through a little pump which is driven by the engine right back to the collector. Figure 3: Again you get mechanical energy. Figure 4 shows a Freon engine, which has been operated in this manner. The advantages of the latter system are that it will use both the direct and diffuse portions of the solar energy and can work on partially or cloudy days. This method of also providing a prime mover allows the use of conventional air conditioning or refrigeration equipment.

Figure 5 shows a Servel refrigerator which we operated about 20 years ago with solar energy. We used a concentrating collector which concentrates the solar energy on a pipe and heated oil up to 800 F and then circulated it around the heat exchanger where the gas flame used to be. This unit operated very satisfactory for many months but it is not an economical system and if we had not had the concentrator in our laboratory we would not have done it. I understand by talking to Dr. Anderson, that they did something similar at Arkla.

For best performance one should use the diffuse portion of solar radiation as well as the direct portion, and therefore non concentrating collectors must be used driving a lower temperature absorption system, of either intermittent or continuous type. An intermittent system consists of two tanks with heat exchanger coi's or tubes. In one of the tanks one may have an ammonia-water solution. Figure 6: Heating the solution with solarly heated water drives out the ammonia, which is condensed in the other tank. This is the charging mode of operation. Letting the solution cool will allow the reabsorption of the ammonia. The evaporation of the ammonia requires heat and this provides the cooling effect desired. We operated one of these intermittent systems for several years. For this system the charging mode was 1/4 of the total operating time. Continuous cooling can be obtained by such a system by using cold side storage such as chilled water which is used while the system is charged again.

The reason we selected ammonia and water are several but among them that this combination can be used both for air conditioning and refrigeration. It is a positive pressure system and small leaks of refrigerants do not render the system inoperative. It is a non corrosive system. The choice of refrigerant absorber combinations is not critical and with new substances and combinations becoming available, we may well use some of them.

Figure 7 shows a half ton unit of the intermittent type. We built several such systems in our laboratory and operated them of solarly heated water. Figure 8 presents the cycle of this system and we can go into detail during the question period. Here operating with an input temperature of 170 F and an output temperature or cooling temperature of 85 F, the concentrations are from about 47 to 60%. This allows operation with temperatures below 200 F which are easy to obtain from stationary flat plate collectors of reasonably economical design and for a good portion of the day and not only during the noon hour when conditions are best. Figure 9 gives the performance of this system.

Cooling can also be accomplished by a continuous system. Figure 10, a schematic of our 5 ton unit consists of a generator which is driven by solarly heated water. This provides the ammonia which is condensed, allowed to flow through the expansion valve into the evaporator where the cooling is done. Then it flows through a heat exchanger to increase the efficiency and into the absorber where the ammonia vapor is reabsorbed in the water. A small pump circulates the solution back into the generator where it starts the cycle over again. The water only flows between the generator and the absorber.

Figure 11 gives the performance during a day operating directly off the solar collectors. If operating off the stored hot water any air conditioning rate could be obtained and maintained.

Figure 12 shows what the equipment looks like. It was built almost 20 years ago with limited funds, using material and parts available. This made the unit much larger than necessary. The collectors are close to the horizontal, inclined properly for summer time operation. For both heating and cooling, thus year around operation, they would be inclined to the latitude plus about 10 degrees. The intended use of the collectors determines the best angle to be used.

To convince people that solar air conditioning and refrigeration units do not have to be large we built a small unit, Figure 13. In this unit since it was used mainly for refrigeration the solar collector and the ammonia generator were combined into one unit. This eliminated the heat transfer loss. Cold side storage was used for cooling when the sun does not shine. The ammonia was generated in the solar collector, then is moved into the condenser, through the expansion valve, into the evaporator where it cools a brine. The brine circulating around a container filled with water freezes it. The ammonia vapor is then reabsorbed in the absorber and pumped back to the solar collector to start the cycle over again.

Figure 14 shows the small ice machine, a four by four foot unit, with the rest of the equipment right underneath or behind it. The whole system is not much larger than the solar collector part.

Figure 15 gives a typical day's performance. It was a day in April giving the solar radiation, the generator pressure, the generator temperature, the amount of ammonia generated and most importantly the amount of ice generated per square foot of this collector. Up to 10:00 A.M. the system and water were cooled and then it started forming ice and continued forming ice until just about sun down. On this particular day the system produced about 2.7 pounds of ice per square foot.

It was mentioned by others that maybe a better route to go is by producing electricity from solar energy and then run conventional air conditioning and refrigeration sytems with electricity. This is far from being practical for economic reasons. Figure 16 shows a system used in our solar house to produce electricity. It is cheaper to use a solar engine and drive a generator, but one can use a solar cell panel like this one. This panel was designed and intended to be used on a satellite. When it was not needed it was given to us by NASA for an indefinite period. The electricity produced by the panel is stored in a battery and then converted as needed from 12 volts DC to 110 volts AC to drive lights, radios, television, small appliances, etc. We have this demonstration but do not recommend this method since the panel cost $3[illegible],000.

Since about 85% of the energy requirements in our home, a typical home, go for hot water, heating and air conditioning, the need for electricity is small.

Last year we put collectors on the roof of the house, replacing the 18 year old ones on the ground, where they really belong and this reduces the air conditioning requirement tremendously since now we have a shaded roof. Recently Popular Science wanted to use our solar house on the front cover of their March issue. When they came to take the picture they felt they could not see the collectors well enough and we had to provide them with a snorkel truck which lifted them three stories up into the air so they could get a good shot of the collectors. The collectors are not too noticeable from the ground. For this reason estetics does not seem to be a problem. Chimneys we accept on roofs, and so most of the chimneys found in South Florida are really water tanks protruding through the roofs.

Figure 17 shows water cooled venetian blinds which can be used to control the amount of sunshine and light to enter the building and at the same time to absorb the rest of the energy to provide hot water for the building. Such combinations of use can be very beneficial and economically advantageous.

Last night it was mentioned several times that social acceptability is necessary. We have run into this. Low cost housing developments with solar water heaters were built a number of years ago and about six months thereafter, the solar water heaters were removed. It took me several years to find out why. The people living in this housing thought they were getting something inferior, thinking that if others can have electric water heaters so should they. The solar water heaters were quietly replaced by electric ones.

To utilize solar energy does not necessarily require ideal systems. Too many people believe that all collectors have to face south and and have to be inclined at the correct angle. My own house with windows and a large oak tree which provides the cooling is not ideally suited for solar conversion. It is an older home and I added a solar booster to my kerosene water heater which has a 30 gallon tank. I put the collector flat on the garage roof which has the wrong angle and is facing west. The collector only is in the sun in the afternoon. It is a poor solar system but an excellent combined system since it reduces my kerosene consumption more than 50%. Thus by adding solar equipment to existing systems great benefits can be obtained.

Right now several bills are before the Florida legislature with regard to solar energy. One proposes to eliminate the sales tax on solar equipment. We have a number of solar water heater manufacturers in Florida. Another proposes to give reductions in real estate taxes for solar equipment used in a building such as water heaters, house heating, swimming pool heating, etc. Another requires that buildings built after a certain date have to have their plumbing arranged so that solar equipment can be added without modification. Another proposes to set up a solar center, etc.

Since many people are entering the field of solar energy with products, some of them inferior, some guidance and protection for the consumer is needed. Standards, codes, certification, such things as UL ratings, etc. may be needed. Care must be taken however in implementing such things since the equipment must be evaluated under the conditions for which it was designed. A swimming pool heater designed to operate under low temperature conditions cannot be compared to a high temperature solar flat plate collector if they are tested under the same conditions, realistic to neither one of them.

I'd like to close on a note which I shall phrase as a question, similar to the one John Yellott raised yesterday. Going back to my Figure 1 showing how little energy fossil fuels can provide from our savings and that we therefore have to learn to live off an income, and our only income of any magnitude being solar energy - "Do we really have a choice?"

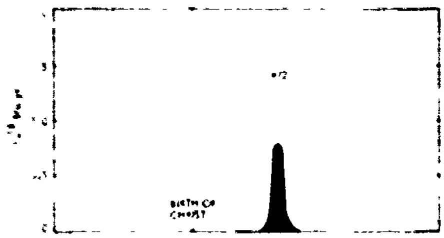


Fig. 1. World Consumption of Fossil Fuels.

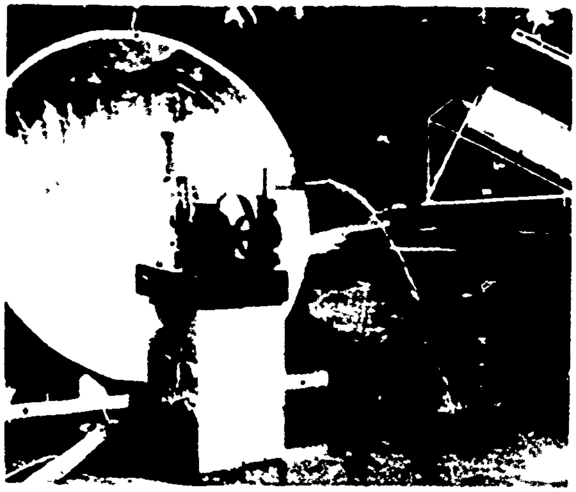


Fig. 2. Solar Stirling Engine.

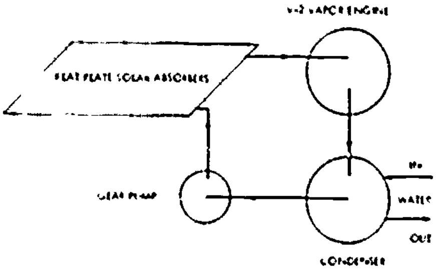


Fig. 3. Schematic Sketch of Low Temperature Solar Power System.

Fig. 4. Freon Vapor Engine.

Fig. 5. Servel Refrigerator Operated by Solar Energy.

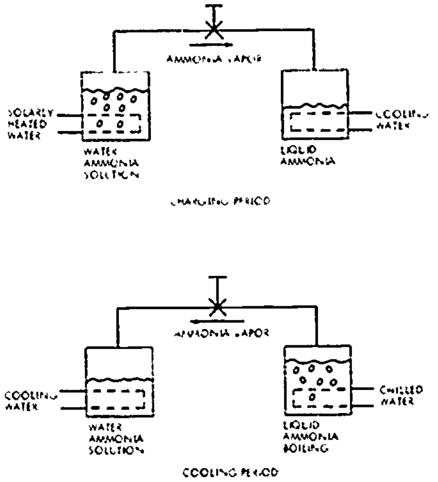


Fig. 6. Intermittent Refrigeration System.

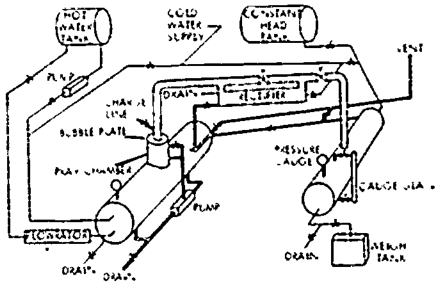


Fig. 7. Half-ton intermittent unit.

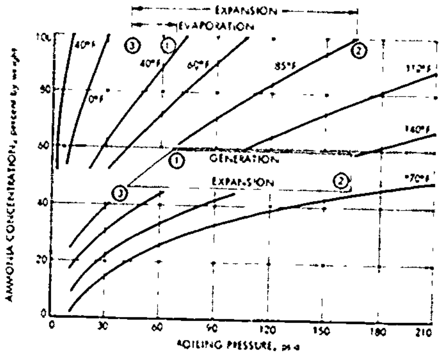


Fig. 8. Pressure-temperature-concentration relationships for absorption refrigeration system using solar-heated hot water for regeneration, liquid ammonia for heat storage are shown above.

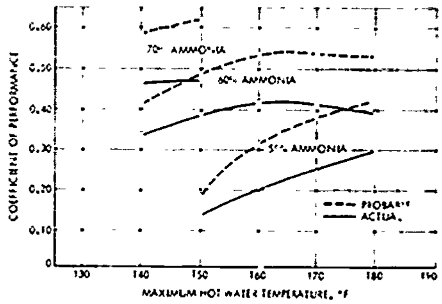


Fig. 9. Two families of curves reflect actual and calculated coefficients of performance fc test apparatus.

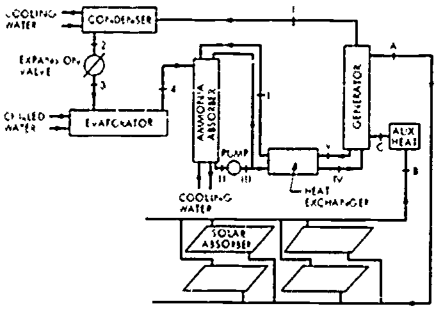


Fig. 10. Flow diagram of a 3 1/2 ton, continuous solar air conditioning system.

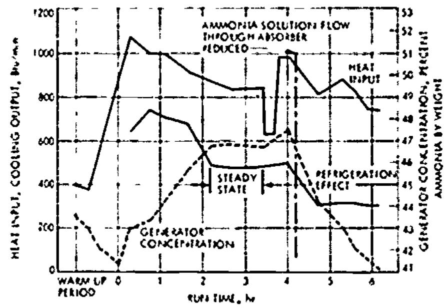


Fig. 11. Performance of a continuous system.

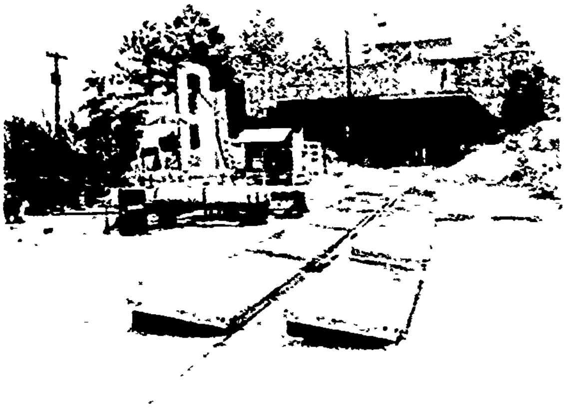


Fig. 12. 5 ton continuous solar air conditioning system.

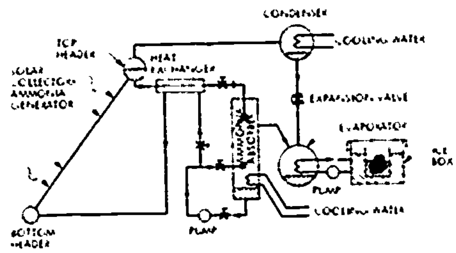


Fig. 13. Small refrigeration unit.

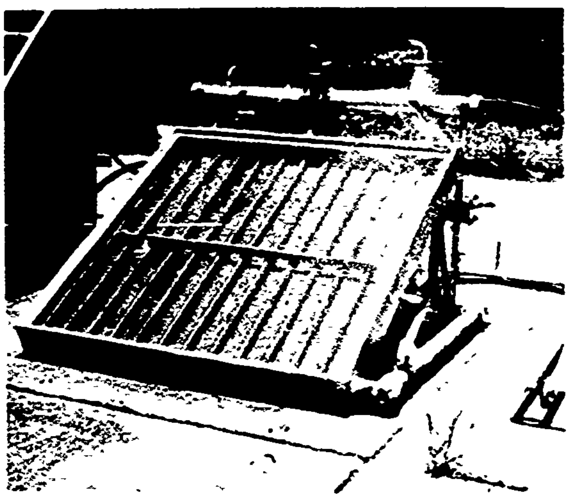


Fig. 14. Solar ice machine.

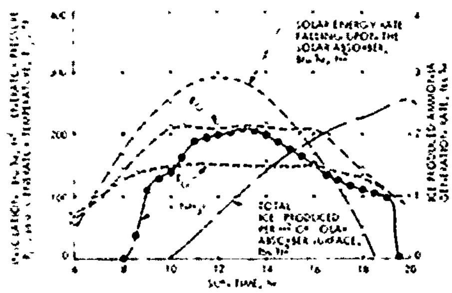


Fig. 15. Typical day's performance of the small unit.

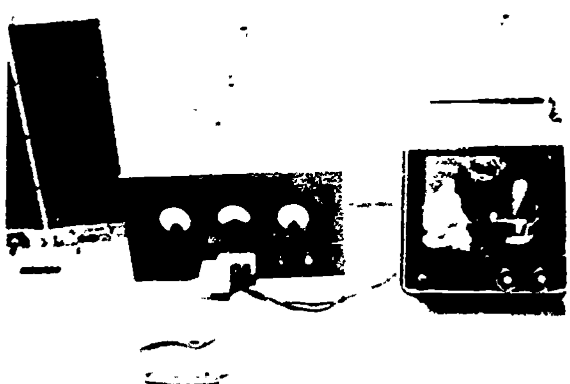


Fig. 16. Solar electrical system.

Fig. 17. Water cooled Venitian blinds.

OPTIMIZATION OF SOLAR POWERED ABSORPTION SYSTEMS

Redfield Allen

University of Maryland

The University of Maryland has for about 5 1/2 months been engaged in an optimization study of solar powered absorption air conditioning, under a grant from the National Science Foundation. Dr. Frederick H. Morse, Dr. Stephen L. Sargent and I are conducting this study with the assistance of three half-time PhD students. Viewgraph 1 presents the objective as the study of the effect of system options and actual process factors on the performance and optimization of solar powered absorption refrigeration. Phase 1 of the study consists of a detailed thermodynamic cycle analysis of absorption refrigeration systems under steady state and diurnal conditions, including collector and tracking analysis. Phase 2 is a combined absorption-collector-storage-tracking, performance and optimization study on a thermodynamic and-heat transfer basis. Phase 3 is economic optimization and consequences.

The absorption system aspect of this study deserves special mention because, while we in a university possess a knowledge of thermodynamics, heat transfer and solar energy, experience in the design and development of absorption units resides in the industry. However, while the absorption industry conducts in-house studies of the type under discussion, the constraints of competition tend to leave the publication of optimization findings in the solar energy application to a non-competitive group such as a university. In this situation it is to be expected that a university would turn to industry for the detailed practical knowledge which only industry possesses. Based on our recent and numerous contacts with the absorption air conditioning industry, we feel optimistic about their sharing practical information of a non-proprietary nature. We turn now to the system under study.

Viewgraph 2 is a solar powered absorption air conditioning system schematic containing the collector, a collector orientation option, the absorption unit and two storage options. The optimization study includes flat plate collectors and concentrating collectors as alternative sources of heat to drive absorption units. Sargent is presently completing modification of a computer program for predicting flat plate collector efficiency for a large range of design configurations and design conditions. The option of collector tracking is included in this study, and companion work is underway to determine the performance parameters of the thermal heliotrope. This a passive bimetallic helical device using the sun to provide shaft power to orient a collector. Since the emphasis at this conference is on cooling, we will not be discussing the heliotrope. At the upper left in the viewgraph is shown the incident solar radiation Q_S. At the lower left is shown the desired cooling effect Q_E. At the collector, the coolant discharge temperature is denoted by T_C. Q_U, at the terminals of the collector, denotes the useful heat output of the collector. At the right in broken lines is shown an optional hot side storage device for smoothing out diurnal variations. In the steady state, this storage device is bypassed and Q_U is converted into generator heat input, Q_G. This heat transfer process is indicated as occurring at the generator temperature level T_G shown at the far left. At the intermediate temperature T_I, condenser and absorber cooling take place. On the right are shown air or water cooling options. At the lowest temperature level T_E, the evaporator heat load, Q_E, enters the evaporator via the connection to the air conditioning coil and the optional cold side storage device. When heat-transfer temperature differences are omitted, the absorption cycle analysis can be fixed by specification of generator, absorber-condenser, and evaporator temperatures T_G, T_I, and T_E, respectively.

Viewgraph 3 repeats the three-tiered temperature format in a schematic comparison between a combined Rankine cycle and vapor-compression (V-C) cycle on the one hand and an absorption cycle on the other. The combined cycle on the left receives Q_S at its collector and the absorption system on the right also receives Q_S at its collector. The collectors supply cycle heat input Q_G at cycle temperature T_G. Overall, each cyclic arrangement produces cooling effect Q_E at cycle temperature T_E. The Rankine power cycle expander produces shaft work which flows to the compressor of the vapor compression cycle. The absorption cycle on the right is a single cycle. It has two intermixed fluid loops, whereas the combined cycle on the left has two separate fluid loops. Heavy arrows denote heat flows of the two cycles. A close one-to-one correspondence is seen when one compares the two systems with respect to these heat flows. At the bottom of the viewgraph we see the theoretical Carnot limit for the maximum possible value of Q_E/Q_G. The limit is based on the combined cycle on the left and is expressed as the product of the maximum possible refrigeration cycle COP and the maximum possible power cycle efficiency. The Carnot cycle analysis yields for a typical set of operating temperatures (200^{0}F, 100^{0}F and 40^{0}F), a maximum value for Q_E/Q_G of 1.26.

We next consider cycle irreversibilities relative to the theoretical Carnot limit. To facilitate comparison with a lithium bromide-water absorption cycle, a combined Rankine and V-C refrigeration cycle is assumed to use water as the working fluid. The vertical bars, in the upper half of Viewgraph 4 represent the magnitude of Q_E/Q_G for the set of operating temperatures 200^{0}F, 100^{0}F, 40^{0}F. The left-hand group of bars is for the Rankine and V-C refrigeration cycle and the right-hand group is for a simple absorption cycle. The tallest bar is the Carnot limit. Introduction of an expansion valve process into the cycle shortens the Q_E/Q_G bar the same small amount for both. This shortening is a measure of the irreversibility. The subsequent addition of an irreversible compression process having an adiabatic wet-compression efficiency of 0.72 reduces Q_E/Q_G substantially. Addition of a Rankine cycle feed water heating process introduces a slight irreversibility in the next step. Finally, introduction of an expansion process with an adiabatic efficiency of 0.72 shortens the bar to the shaded length. On the right, addition of the absorber and generator also shortens the bar to the shaded length. It is seen that by choosing compression and expansion efficiencies of 0.72 on the left, the Rankine cycle and V-C refrigeration cycle irreversibility has the same overall value as that of the simple absorption cycle.

The lower portion of Viewgraph 4 is a plot of Q_E/Q_G versus the source temperature T_G. The intermediate temperature is assumed to be fixed at 100^{0}F and the evaporator temperature is assumed to be fixed at 40^{0}F. At an abscissa value of 200^{0}F, the Carnot, the V-C/Rankine, and the absorption ordinate values, respectively, correspond to the bar chart results. In theory, the Carnot cycle and combined V-C/Rankine cycle have Q_E/Q_G trends starting at zero at T_G = T_I = 100^{0}F and these trends increase steadily as T_G increases. But, in theory, the absorption cycle does not produce any Q_E/Q_G until T_G exceeds 175^{0}F. Thereafter, as T_G increases, Q_E/Q_G rises sharply and forms a "knee" as it levels out. From T_G = 175^{0}F to T_G = 200^{0}F, the irreversibility of the absorption cycle decreases. Thereafter, the irreversibility increases as the curve levels out and the corresponding Carnot values continue to increase.

Viewgraph 5 shows a conventional absorption system with a subcooling heat exchanger on the left, between the condenser and the evaporator, and a liquid-liquid heat exchanger on the right between the generator and the absorber. This is a modified absorption refrigeration system.

Continuing with a discussion of equilibrium thermodynamic calculations and disregarding pressure drops or temperature drops, we turn to results for simple and modified cases. Viewgraph 6 shows a lithium bromide-water case based on an intermediate temperature of 80°F and an evaporator temperature of 40°F. The upper part of the diagram is marked T_G/80/40. The upper diagram shows the Carnot limit and the performance of a lithium bromide-water absorption system extending out to the crystalization limit. A slight improvement is shown with the addition of a liquid-liquid heat exchanger. The middle diagram shows the mass flow from the absorber to the generator, M_G, divided by the rate of flow through the evaporator, M_E. As the generator temperature is reduced from 200°F, this ratio rises at an increasing rate. The ratio is independent of the presence or absence of a heat exchanger in the system. More pumping power is required and a larger liquid-liquid heat exchanger is required as T_G is reduced. The bottom diagram shows the ratio of absorber heat transfer, Q_A, to evaporator heat transfer, Q_E. Absorber heat transfer is relatively insensitive to a change in generator temperature and is reduced somewhat by the addition of the liquid-liquid heat exchanger. The addition of the liquid-liquid heat exchanger also reduces the amount of heat transfer in the generator.

Viewgraph 7 contains a family of calculated results for a lithium bromide-water cycle. The designation in the upper left-hand corner of the top diagram, T_G/T_I/50 specifies a 50°F evaporator temperature. Condensing temperatures, T_I, are 80°F, 100°F, and 120°F. Throughout, the ideal liquid-liquid exchanger improves performance, especially at higher condensing temperatures. It is notable that the cutoff point where the degassing breadth goes to zero shifts to higher temperatures as the condensing temperature is raised. Referring to the three diagrams from top to bottom, it is seen that as the evaporator temperature is lowered, the coefficient of performance, Q_E/Q_G is reduced somewhat. The evaporator temperature is reduced in five degree increments in contrast to the larger increments assigned to the condenser. Reading from the bottom to the top we see that by raising the evaporator temperature, the cycle can be operated at lower generator temperatures.

Results for the ammonia-water cycle are shown in Viewgraph 8. The vertical span between the solid line and the broken line is the penalty for not using a liquid-liquid heat exchanger. The penalty is greater than it is for the lithium bromide-water cycle results shown in Viewgraph 7.

The general configuration of the curves is the same for the ammonia-water and lithium bromide-water cycles. The point at which Q_E/Q_G goes to zero is located at a slightly higher generator temperature in the ammonia-water case. The cycle operating band lies between this lower generator temperature limit and a practical upper generator temperature limit. The practical upper limit is dictated by the occurrence of crystallization in the lithium bromide-water cycle and by the occurrence of decomposition of ammonia in the ammonia-water cycle. This ends the discussion of absorption cycle calculations.

The solar collector has been very carefully modeled by Sargent based on a general heat transfer program developed by Beckman at the University of Wisconsin. The cross-section of a typical water-cooled flat plate collector is shown in Viewgraph 9. The collector model is being extended so as to take into account not only the temperature distribution in the cross-section normal to the direction of fluid flow but also the temperature distribution in the direction of fluid flow. The lower part of the diagram shows the span between the inlet and exit of one flow passage. The upper portion of the diagram shows a collector including cover plates, absorber plate, and insulation. In this view node 6 identifies the cooling fluid, node 8 identifies the outside of the collector, and nodes 1 and 2 identify ambient and sky respectively. The first step in running this program, apart from trial and error exercises, has been its verification for a simple collector configuration. Calculated efficiency results appear in Viewgraph 10. The quantity Q_U/Q_S is collector efficiency. Two computer calculations of collector efficiency versus fluid temperature rise are reported for an assumed incident radiation of 300 BTU per square foot hour, fluid inlet temperature 70 degrees, an ambient of 70°F and a sky temperature of 40°F. The load on the collector was varied by varying the fluid flow rate. The lower efficiency curve is for the case of a flat black absorber plate with one glass cover. The flat black solar absorptance is 0.92. The higher efficiency curve is for a selective coating having a solar absorptance of 0.92 and an infrared emmittance of 0.10. Viewgraph 11 shows the fluid temperature trend versus distance in the flow direction. The broken line represents the tube temperature, whereas the solid line represents the fluid temperature. The tube temperature is 3°F to 30°F higher than the fluid temperature. Fluid flow in the tubes is laminar. Viewgraph 12 is an itemization of collector parameters and other features that can be included in the collector computer program.

Viewgraph 13 presents a system consisting of a collector, an absorption unit and storage. Also presented are typical collector performance curves and typical absorption cycle performance curves, with notations on storage ranges lying in between collector and absorption cycle curves. The schematic diagram at the top shows solar energy input Q_S falling on a collector which delivers useful heat output Q_U to the absorption unit and/or hot-side storage device S_H. The absorption unit carries cooling load Q_E and/ or cools the medium in storage device S_C. Below this schematic diagram, are shown typical collector efficiency curves plotted versus fluid outlet temperature T_C for a low technology flat plate collector, a high technology flat plate collector, and a concentrating collector, based on a nominal mid-day insolation level. At the bottom of the viewgraph are shown plots of absorption cycle performance parameter QE/QG versus generator temperature T_G. Results for the modified lithium bromide-water cycle and the modified ammonia-water cycle are represented by solid lines and broken lines respectively. The generator temperature abscissa at the bottom of the viewgraph is vertically aligned with the collector fluid outlet temperature abscissa. With this vertical alignment in mind we can consider a horizontal span formed by the abscissa value where Q_E/Q_G goes to zero for an absorption cycle and the abscissa value where Q_U/Q_S goes to zero for a collector. In the case of the absorption cycle at T_I = 100°F and the low technology flat plate collector, the horizontal span is short. Within this narrow temperature range, system efficiency has a low peak value due mainly to the low collector efficiency. Use of the high technology collector would improve system performance and permit operation over a wider temperature range on the abscissa. However, crystallization in the lithium bromide-water cycle places an upper limit on this temperature range and precludes use of the high temperatures attainable with the concentrating collector. The ammonia-water absorption cycle can be operated up to a decomposition limit of 350°F to 400°F and could therefore utilize the higher fluid outlet temperatures produced by a concentrating collector. With the single-stage absorption cycle incorporating a liquid-liquid heat exchanger, the absorption performance curve has a distinct "knee." Once this knee is crossed in the direction of increasing generator temperature, an overall performance improvement can only be obtained by use of a more sophisticated solar collector. Use of a dual-effect absorption cycle or a cycle equipped with overlapped generator and absorber functions would enable the absorption cycle performance to respond positively to higher collector fluid outlet temperatures. Also, higher collector fluid outlet temperatures will have a more significant beneficial effect when the finite temperature differences of the heat transfer processes are included in the analysis.

Our future collector work will include modelling the high-technology flat plate collector features appearing in Viewgraph 14. Concentrating collectors will also be modelled. In our future absorption work we will continue with modifications of absorption cycle calculations including dual-effect generators and overlapped generator and absorber. We will further consider finite temperature differences in heat transfer processes and include pressure drops. Other viable absorption pairs will be studied. We will undertake the modelling of system capacity response to changes in collector temperature and connect the cycle model with the collector model. Finally, we intend to interact with absorption refrigeration manufacturers in evaluating the effect of actual equipment process factors on calculated performance.

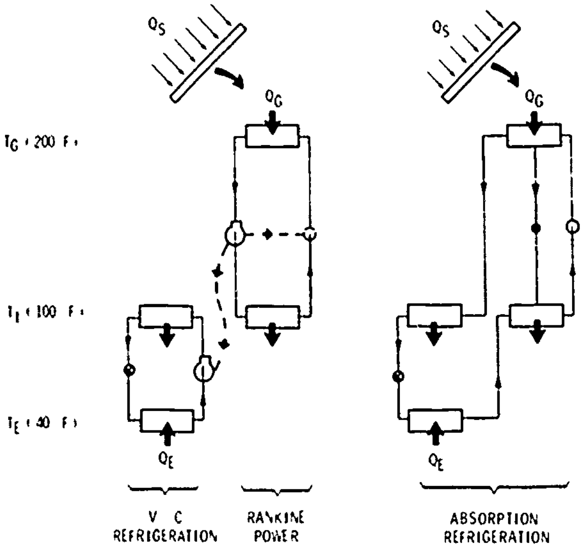
OBJECTIVE - TO STUDY THE EFFECT OF SYSTEM OPTIONS AND ACTUAL PROCESS FACTORS ON THE PERFORMANCE AND OPTIMIZATION OF SOLAR POWERED ABSORPTION REFRIGERATION

PHASE I: DETAILED THERMODYNAMIC CYCLE ANALYSIS OF ABSORPTION REFRIGERATION SYSTEMS UNDER STEADY - STATE AND DIURNAL CONDITIONS, AND COLLECTOR AND TRACKING ANALYSES.

PHASE II: COMBINED (ABSORPTION, COLLECTOR, TRACKING) PERFORMANCE AND OPTIMIZATION ON A THERMODYNAMIC BASIS.

PHASE III: ECONOMIC OPTIMIZATION AND CONSEQUENCES.

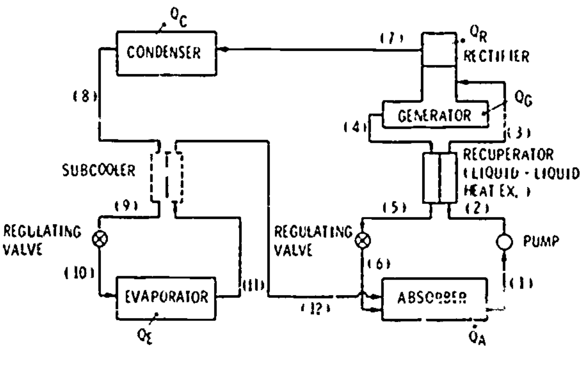
Viewgraph 1. Optimization Studies of Solar Absorption Air Conditioning



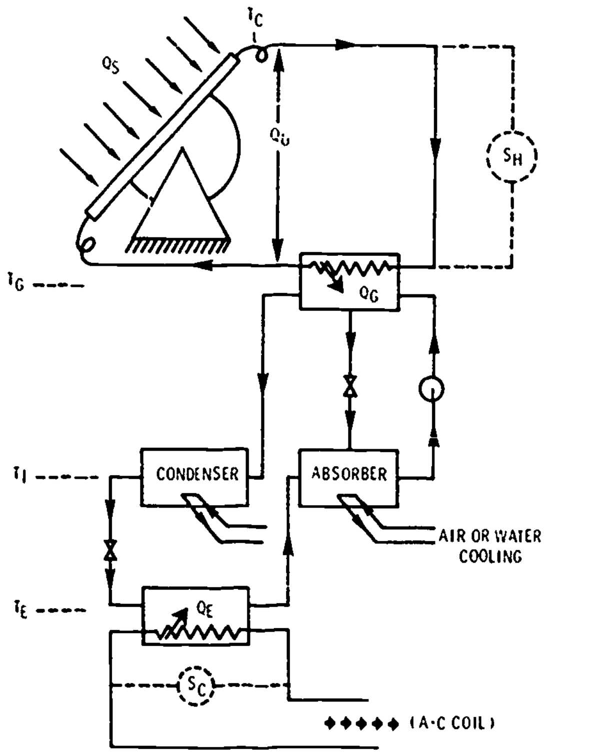
CARNOT LIMIT $\frac{Q_E}{Q_G} = \frac{T_E}{T_I - T_E} \cdot \frac{T_G - T_I}{T_G} = 1.26$

200 100 40

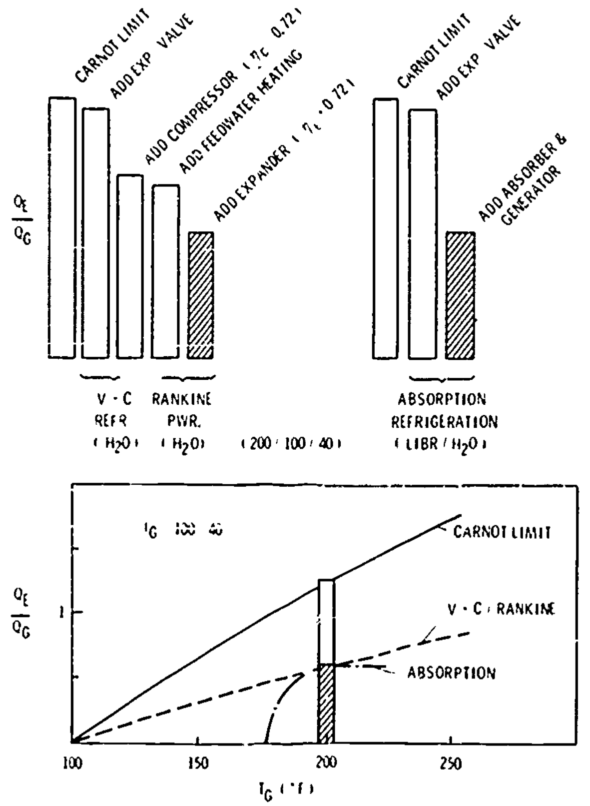
Viewgraph 3. Combined-cycle and Absorption-cycle Schematics.



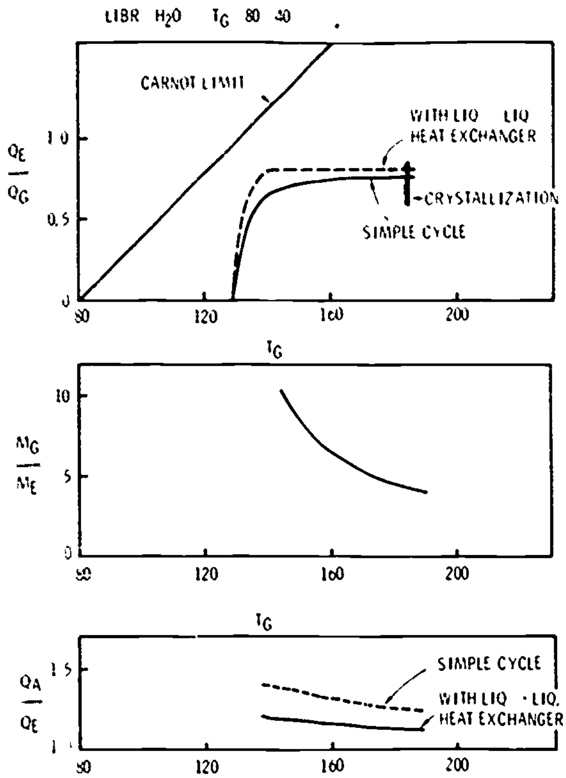
Viewgraph 5. Modified Absorption Refrigeration System.



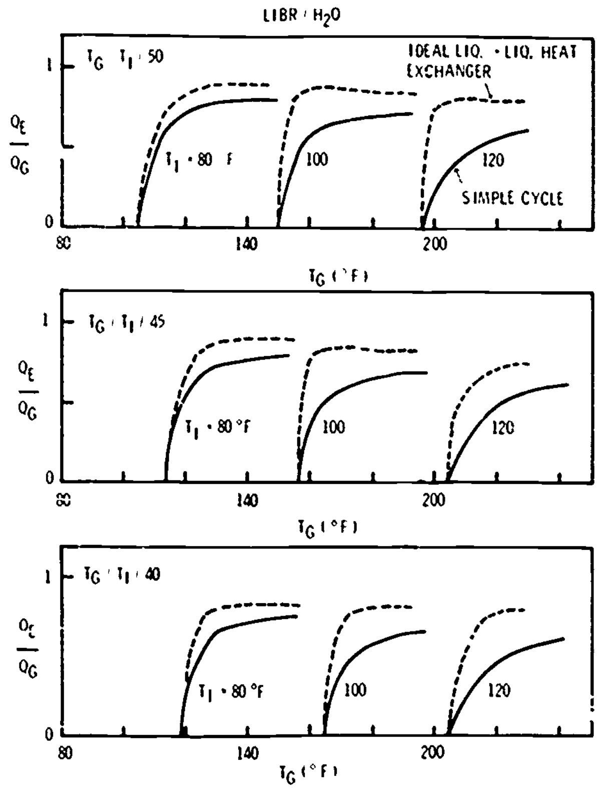
Viewgraph 2. Solar Powered Absorption Refrigeration System (With Storage).



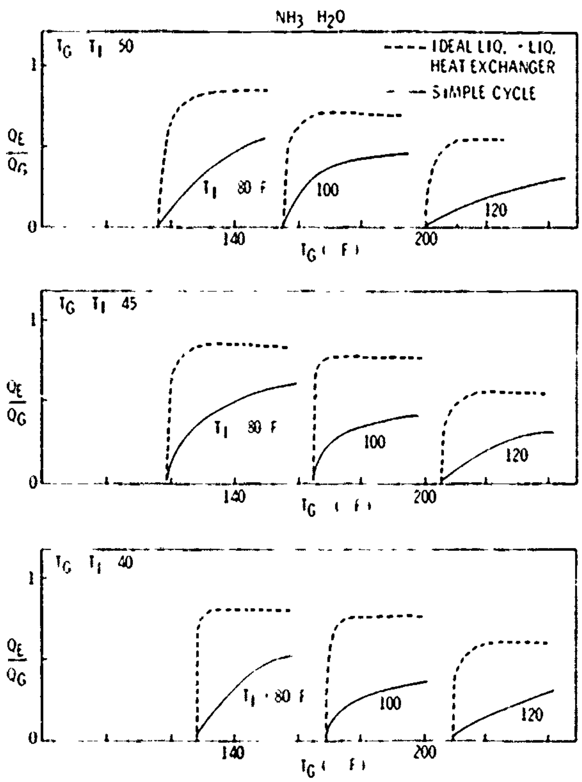
Viewgraph 4. Combined-cycle and Absorption-cycle Performance.



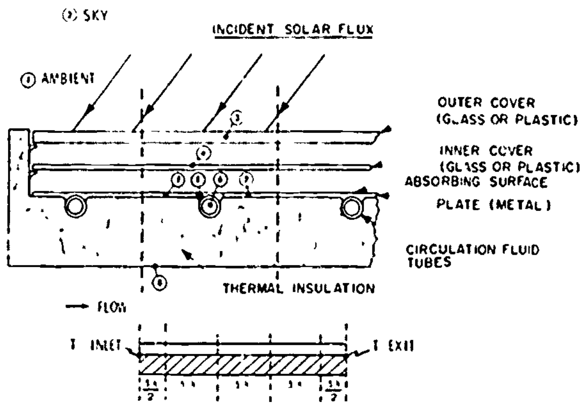
Viewgraph 6. Some Performance Characteristics of a Lithium Bromide-water Absorption Cycle.



Viewgraph 7. The Effect of Cycle Temperatures on the COP of a Lithium Bromide-water Absorption Cycle.



Viewgraph 8. The Effect of Cycle Temperatures on the COP of an Ammonia-water Absorption Cycle.



Viewgraph 9. Typical Flat Plate Collector Configuration.

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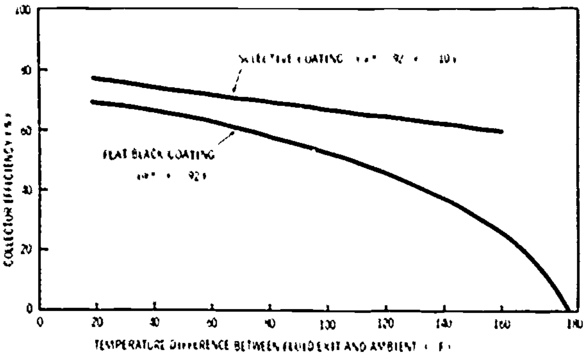


Viewgraph 10. Computed Collector Efficiency as a Function of Fluid Exit Temperature.

COLLECTOR PARAMETERS

- PLATE ABSORPTANCE AND EMITTANCE (LW & SW)
- NUMBER OF COVERS
- COVER TRANSMITTANCE AND REFLECTANCE (LW & SW)
- INTERNAL CONVECTION COEFFICIENTS
- INSULATION THICKNESS AND CONDUCTIVITY
- PHYSICAL DIMENSIONS (TUBE AND COVER SPACING, ETC.)
- PLATE CONDUCTIVITY AND SPECIFIC HEAT
- GEOMETRIC ORIENTATION

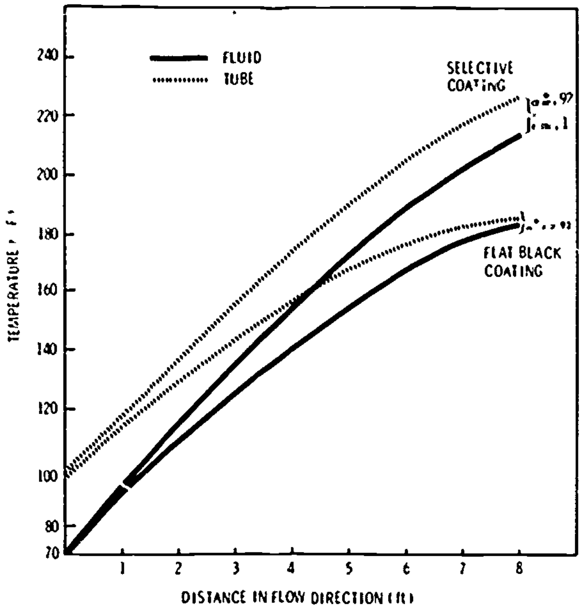
MODEL CAN INCLUDE

- TIME - VARYING DIRECT AND DIFFUSE SOLAR RADIATION
- NODAL THERMAL CAPACITANCE
- TIME - VARYING LW SKY RADIATION
- SPECULAR AND DIFFUSE SW AND LW REFLECTIONS
- ANGULAR - DEPENDENT REFLECTIVITY
- FLUID INLET TEMPERATURE AND FLOW RATE
- FLUID PROPERTIES AND HEAT TRANSFER COEFFICIENT
- 2 OR 3-DIMENSIONAL HEAT FLOWS

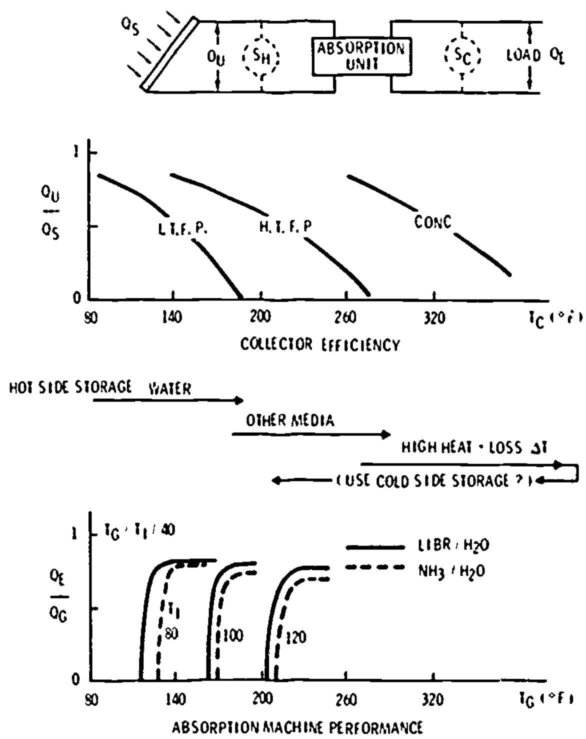
Viewgraph 12.

- SELECTIVE SURFACES
- HIGH TRANSMITTANCE COVERS
- OPTIMUM NUMBER OF COVERS
- HONEYCOMBS BETWEEN PLATE AND INNER COVER
- AIR CELLS BETWEEN COVERS
- OPTIMUM COVER SPACING
- PARTIAL EVACUATION
- DIURNAL TRACKING

Viewgraph 14. Collector Improvements.



Viewgraph 11. Computed Collector Tube and Fluid Temperatures in the Flow Direction.



Viewgraph 13. Combined Collector and Absorption System Performance.

SOLAR ASSISTED HEAT PUMPS

Stanley Gilman

Pa. State University

What I'm going to talk about is different from what has been discussed so far. It's not about absorption machines or residences, but about evaluation of a solar energy, heat pump assisted, heating system in a commercial office building. The key components are electrically driven water source heat pump units. The pioneers in this area were Bridgers and Paxton, as pointed out by John Yellott in his presentation.

What really is the problem we're trying to solve? It is simply this: A mechanical consulting engineer wants to design a commercial office building, solar energy, system. He goes to the ASHRAE Handbook and there isn't a word in it on how to design such a system. So the architect, reading all this information in the newspapers about solar energy and its potential, says: "Can you design one?" And the consulting engineer says: "No, I really can't, there just isn't any information." "Will it work?" "I am not really sure." "How much will it cost?" "I don't know."

So the architect goes to the builder and says: "I've got a very exciting proposition for you. It's a solar energy commercial office building system. However, we have a few problems. We don't know how to design it. We don't know if it will work. We don't know how much it will cost. But we think it's an exciting project, and we'd like to do it." The builder says: "Not on your life with my money, give me a conventional system."

The object of this research proposal which has been made to NSF, and for which a grant award has now been made, is to fill this design data gap in the solar energy assisted heat pump system literature. We hope to fill it quickly, so that design information can get into the hands of practicing engineers soon. The building we will evaluate and obtain generalized information on is in Albuquerque, New Mexico, and is shown in Figure 1. This is the Solar Building of Bridgers & Paxton, Consulting Engineers, a firm of mechanical consulting engineers in the heating, ventilating, air conditioning industry. Frank Bridgers, one of the two partners in the operation, is a past president of ASHRAE. In 1955 the firm designed and had constructed this building for their own use. The water-type, flat plate, solar collector occupies the entire south facing wall. It is tilted back 30 degrees from the vertical. The building has 4300 square feet of floor area, and the solar collector is 750 square feet, underground water storage tank holds 6000 gallons.

During the 1956 - 1957 winter heating season, Bridgers and Paxton collected some operating data and presented a paper on this subject at the 1958 meeting of ASHRAE (Bridgers & Paxton, 1958). Some of the inconsistencies in the results were attributed to the fact that the weather station was three miles away. Nevertheless, the solar collector appeared to supply about 50% of the total heating requirements.

In 1957, the economic analysis could not justify the system, but reference even then, 17 years ago, is made in the paper to the future potential of solar energy; viz, with the diminishing supply and the potential increase in the price of fossil fuels, such a system might indeed have tremendous potential in the future.

Figure 2 shows a floor plan of the Solar Building. There are five water-to-air packaged heat pump units and one 7-1/2 ton water-to-water heat pump, which together combine to heat and cool the building.

The summer cooling mode is shown in Figure 3. The water-to-water heat pump in the center supplies chilled water to the air handling unit in the upper right. There are a total of five water-to-air heat pumps of the type shown in the lower right. The solar collector is not in the circuit as it was used for winter heating only. In the summer, the closed circuit evaporative water cooler was used to reject heat when necessary to keep the storage tank from exceeding specified limits of temperature. The loop water system which runs throughout the building must be maintained within temperatures at which it can be used as either a water source or a water sink. This is in the general range of 40^0 to 100^0 F.

The major heating mode is illustrated in Figure 4. In this case, the water-to-water heat pump is supplying hot water to the air handling unit in the upper right. On heating, all the heat pumps withdraw heat from the water storage tank. During the night, the solar collector is by-passed to prevent thermal radiation to the cold sky and hence loss of heat from storage.

The water-to-air heat pump cycles are shown in Figure 5. On the left is the cooling cycle. In the process of delivering cool conditioned air to the space, the loop water heat exchanger acts as a refrigerant condenser. Hence, it rejects the heat absorbed from the space, plus the heat equivalent of the compressor power input, into the water loop.

The heating cycle is shown in the right hand portion of the figures. The warm conditioned air supplied to the space is comprised of the heat absorbed in the water coil (chiller) by the refrigerant, plus the heat equivalent of the power input to the refrigerant compressor.

Consequently, the ideal situation exists when two units of the same size are on heating and one is on cooling. At this time, the heat rejected into the water loop unit on cooling is balanced by the heat absorbed by the two units on heating and the loop water temperature stays in the range of 60^0 F to 90^0 F.

With regard to a typical commercial office building, heat from the interior zone is being continually rejected into the loop water. On, say, a 30^0 F outdoor temperature and sunny day, all exterior zone units are withdrawing heat from the loop/storage tank system at 6 A.M. As the sun rises, the east zone eventually requires cooling, so this heat is rejected into the loop. Around noon, the south exposure requires cooling, and so on.

In the meantime, as the day progresses the people and lighting loads require more cooling effect; hence, around 4 to 8 p.m. considerable heat is being placed into storage. During the period of about 10 a.m. to 2 p.m. the solar collector is also putting much heat into the water storage tank, so the temperature of the storage water rises as the day progresses.

During the evening and throughout the night, the only source of heat is the water in the storage tank. The heat pumps gradually withdraw this heat to supply the heating demands, and the tank water temperature gradually declines until the cycle repeats itself at sunrise the next day.

A simplified schematic of such a system is shown in Figure 6. The major elements are the solar collector, the flywheel effect made available by the water storage tank and the heat pump units. The lower the water temperature going to the solar collector, the more efficient it is. Since such low temperature water, say 60^0F, is not useable for heating a space, the heat pump units are the key elements in the total performance of the system, as they can use this water as a source and supply 100^0F, or higher, air temperature to the spaces for heating.

The objective of this NSF sponsored research program is to study and understand the dynamics of such systems. Then, after collection and correlation of actual operating data with computer modeling of the system, design information will be developed for consulting engineers to use for such systems regardless of the geographical location. In addition, the cost data will be obtained so life cycle costs analyses can be made and the optimum sizes and configurations of solar collector, water tank, etc., selected.

The results of this research should help fulfill the NSF objective, viz; to promote the widespread application of solar energy systems.

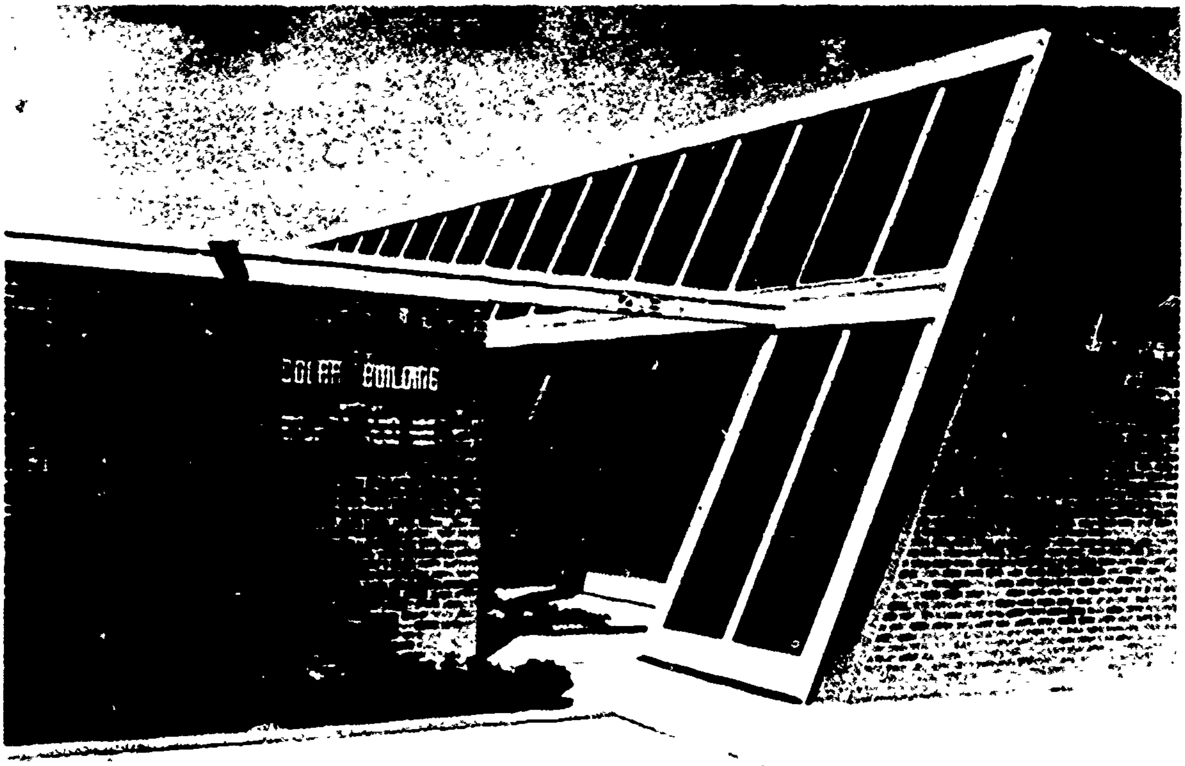


Fig. 1. Bridgers and Paxton Office Building.

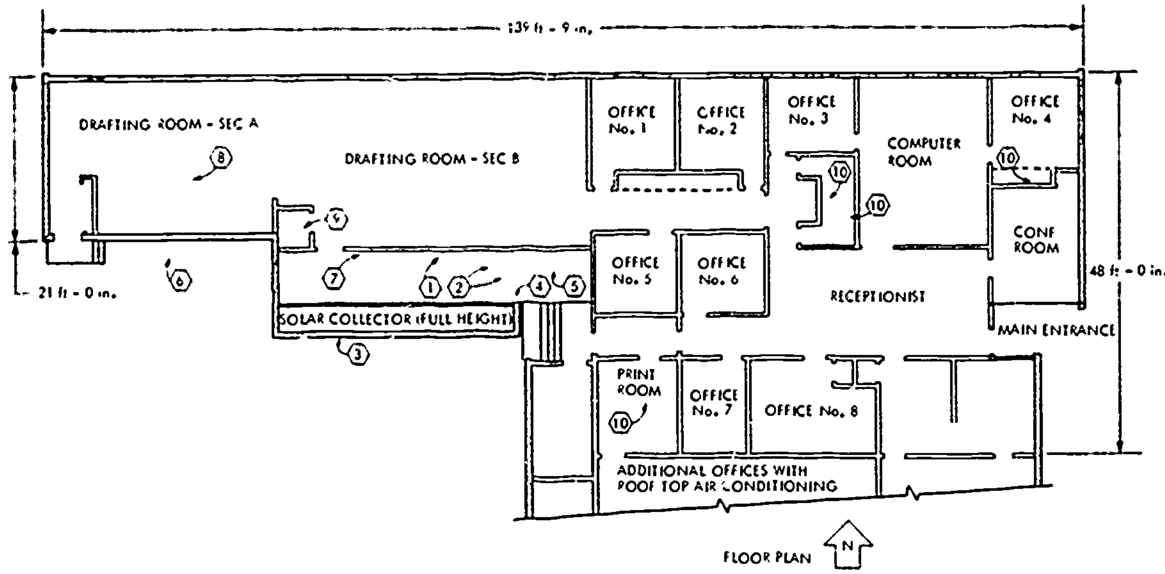


Fig. 2. SOLAR OFFICE BUILDING
OF
BRIDGERS AND PAXTON, CONSULTING ENGINEERS INC
213 TRUMAN N.E., ALBUQUERQUE, NEW MEXICO

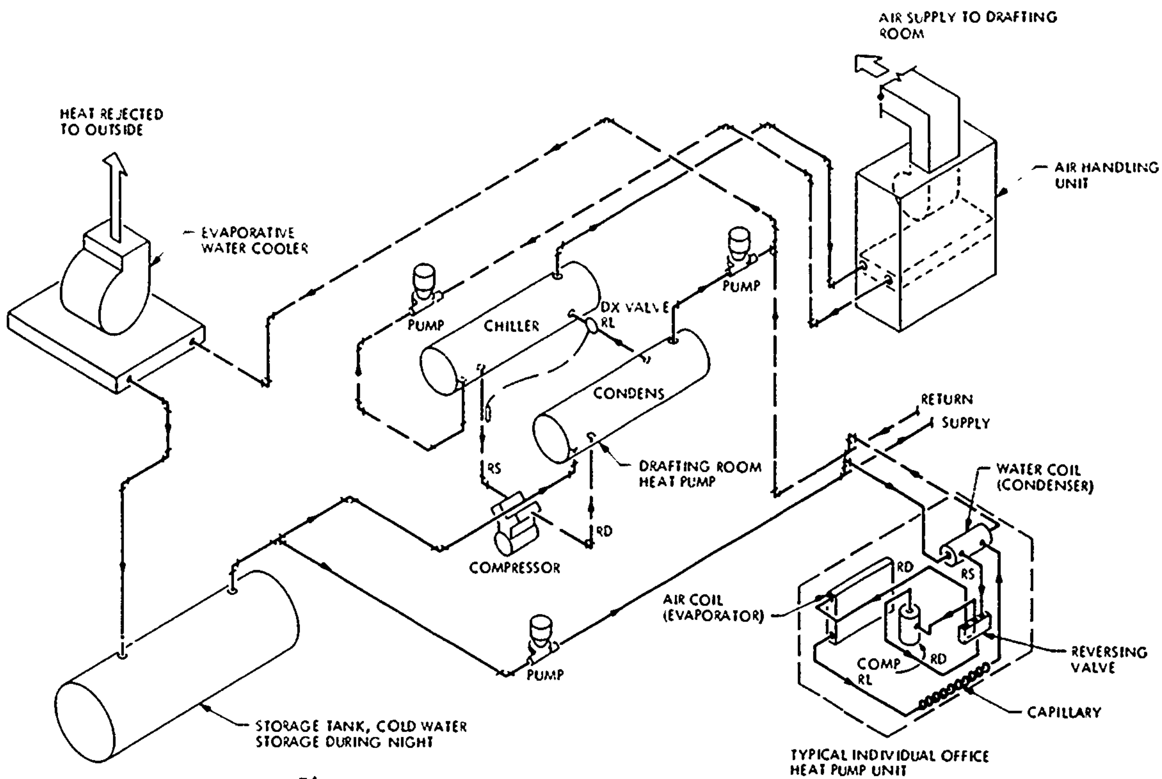


Fig. 3. COOLING WITH HEAT PUMPS

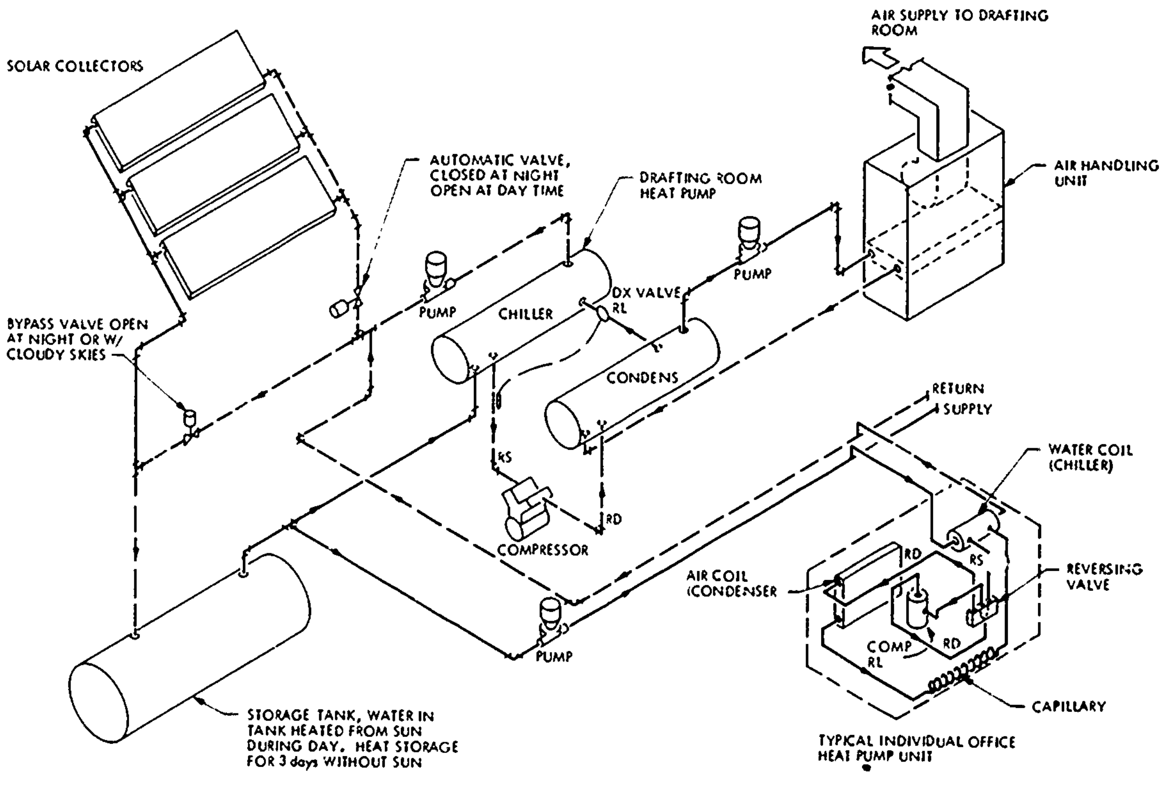


Fig. 4. SOLAR HEATING WITH HEAT PUMPS
HEAT EXTRACTED FROM WATER IN STOR TANK

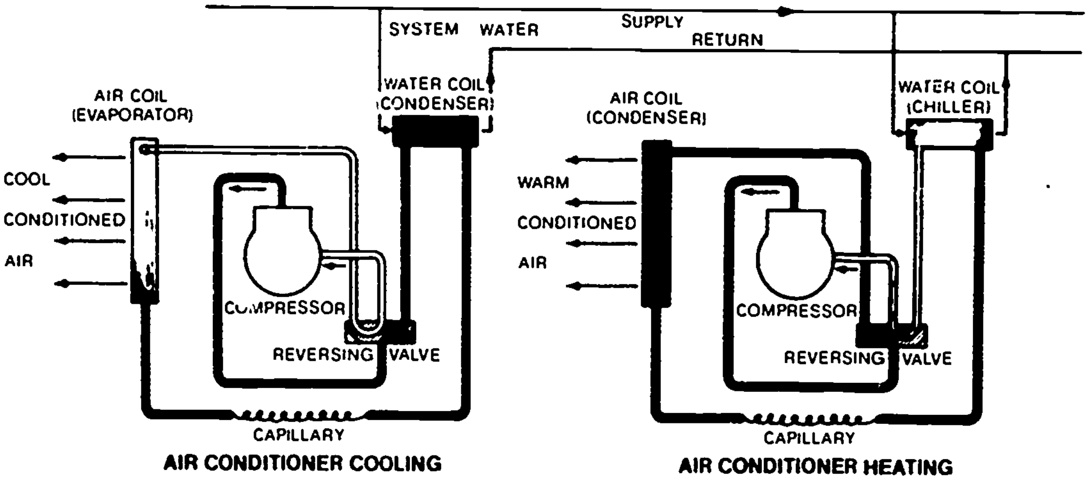


Fig. 5. Water-to-Air Heat Pump Cycles. Cooling on Left. Heating on Right.

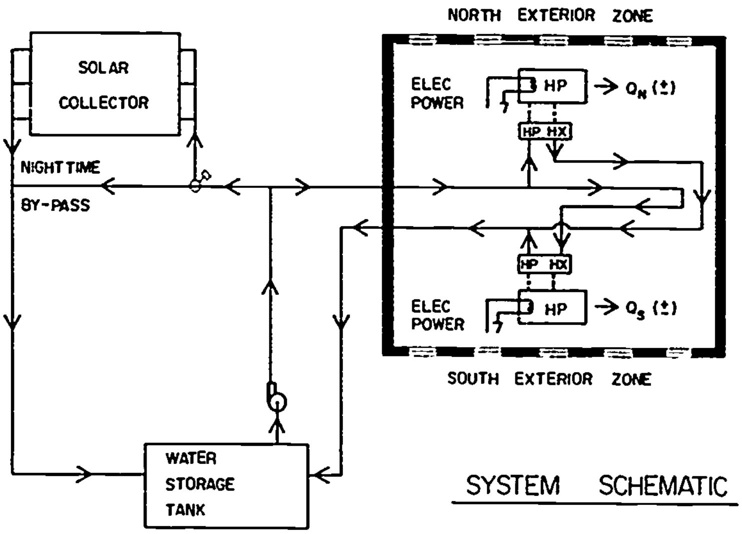


Fig. 6. System Schematic.

Commentators: J. Marx Ayres (Ayres and Hayakawa)

Sanford Weil (Institute of Gas Tech.)

Questions and Answers:

Marx Ayres: I would like to make some starting comments before going to the questions. In 1948 Frank Bridgers and I were classmates at Purdue University, and I was living in a solar heated house on the campus. Frank Bridgers was one of the fellow researchers and we discovered we had to put refrigeration inside of a south facing solar house in order to bring temperatures down. It was a great discovery in 1958. I and really delighted to see that Frank, who put his own money into that little building, is now going to have that effort examined carefully and published again. I think that's a great tribute to his foresight.

I would like to say also that the consulting engineers look on the panel and other solar components emerging here as products to be evaluated in a system of many components in buildings. Today, the technology calls for life cycle costing, with the use of computers over the entire life of the buildings and the solar component is in that building as an option against many many other options. So it will have to stand on its own two feet in the real life cycle costing. The only other thing I'd like to say is that we've looked at a lot of this stuff on the roofs and I work with architects all the time and they won't accept the aestetics that you fellows are talking about. I know one type of a force that won't accept them and that's our California earthquakes. We toss things around on roofs so there is another cost here, in bracing and hiding that stuff on these roofs.

I'd like to direct the first question to Stan Gilman. The question is, "What provisions will be made for heat supply when extreme low temperatures and no heat in the storage tank prevail? What electrical costs can be anticipated versus natural gas heating and conventional heating?"

Gilman: For periods of extremely low temperatures or several days of cloudiness, a source or supplementary heat (oil, gas, liquified petroleum, or electricity) will have to be used. This is why we are talking about solar energy assisted heating systems. If you designed a collector to supply all of the heat required at all design conditions, you would collect too much thermal energy at all other times, and would have to reject it to the atmosphere through the evaporative water cooler. One of the things we will be trying to determine is the optimum amount of solar collector area. Off hand, I would judge that a good target would be 50% of the winter heating requirements. Regarding electric power consumption, much depends on the specific application. With water-to-water heat pump COP's of 4 to 5, system BTU requirements in the range of 10% to 20% of conventional independent heating and cooling systems should be attainable.

Ayres: While you were making your presentation, many of us recognized the application as being similar to the water heat pumps offered by many manufacturers such as California Heat Pump, Singer, and American Standard and so on, and one question is directed to you here with regard to Singer, where there has been quite a bit of published information on that and the concern is that you have examined that.

Gilman: Somewhat less than half of the total cooling capacity is supplied by water-to-air heat pumps of the types mentioned. They do not happen to be Singer units, but all of these packaged heat pumps have very similar performance characteristics. I am very familiar with all brands. The majority of the cooling capacity is supplied by a water-to-water heat pump. This is an applied or built-up system custom designed for the application. The object of the program is not a study of heat pump performance. Rather it is a study and optimization of the basic elements (collector, storage tank and heat pumps) as a complete system, together with the determination of design criteria to obtain the maximum performance at the lowest life-cycle cost.

Ayres: Thank you. I guess we in California like to think we've invented everything, with names like "California Heat Pumps." In any event, those of you who are not familar with that cycle. they've put on the roof a boiler or a cooling tower and tie it into that circuit and what's being disucssed here is the ability to get into that water circuit and use a solar collector. The other has to do with the large commercial buildings always being in this multiple heating and cooling mode which takes me back to the question of stressing the initial energy conservation approach of the building to minimize these loads, and those of you who are not dealing in the commercial field, know there are many many factors besides the simplicity of the house which is just a shell response. I believe we have one final question for Gilman and that is, "Why did Bridgers & Paxton shut down their solar facility?"

Gilman: They ran one winter heating series of tests and proved the principle. It was operated for about eight years after that but had to be manually operated to a certain extent. For example, if there was danger of freezing, the collector had to be drained. When you drain water and refill it in a device, getting all the air (a non condensable) out can be troublesome and time consuming. In addition, the rubber return bands case hardened and some leaks sprung up in the system. Since the system required manual attention and labor costs were rising, they simply put the collector on permanent by-pass.

Weil: At IGT, quite often we have been approached by people with ideas on air conditioners, which is one reason why I'm up here. They have new ideas on how to achieve air conditioning, and are often showing us machines, nothing to do with solar energy, usually gas fired. People build these machines and they to prove they have a valuable machine, they say, "see, if you put your hand there, the air is coming out cold." Then it takes us a long time to go back through some calculations and find out just what we are getting in terms of real numbers besides just something that will cool a hand. I'd like to make it my first question to Farber. In the ammonia water machine that was described, unless it was in the fine print in the slides that we didn't see, we have no idea at all of any measure of the efficiency, COP, what everyone will wish to describe the performance of the machine, several people have indicated they would like an idea of how well it performs.

Farber: Actually, the data was in the slides that did not come through and were skipped. Much of this data is in the literature, and you can look it up. To give you ideas, intermittent systems operate at a COP of about .4 to .6 and even under certain conditions to .7, continuous systems operated from about .3 to .5. Again I might mention, it depends upon how you operate these systems. If you tie it directly to the solar variation, obviously during the noon hours, you get maximum output. On the other hand, you can go to a storage system and provide max. cooling when desired. We used hot water, and you can operate the system anytime you want and your solar radiation is really not tied in with the actual peak capacity and performance of the refrigerator.

Question: Another question that was asked was, what size ammonia water systems can be fabricated and still stay within the ASME code maximum of six inch diameter vessels?

Farber: Well, you don't really have to stay within the six inch diameter vessel only if you want to bypass the code, but if you abide by the code, rules and regulations, you can go to larger pressure vessels.

Weil: To present the data on ammonia absorption systems, when the collector was integrated with the ammonia system, showed a two hour lag for the beginning of generation to the start of refrigeration production. Do you have similar data for the system in which the generator is heated by hot water?

Farber: Yes. Well with hot water it's a very short time. Maybe five or ten minutes, just enough to heat up the system, because you have the hot water. What you really have with solar energy is early in the morning, the collector is hit by the sun at a very poor angle. So the output of the collector is very low and it takes quite a considerable time to get it up to temperature.

Weil: Several questions were addressed to Allen, and I would also like to ask some questions on my own. In this first and second law analysis of the absorption cooling machine coupled with solar collectors, the first question I'd like to bring up, is: What phenomenon determines that the lower generator temperature limit of operation is so strongly related to the condensing temperature?

Allen: The lower generator temperature limit of operation of an absorption cycle is determined by two quantities. These quantities are the presssure in the generator and the concentration of the solution coming from the absorber. The lower limit is therefore dependent on condensing temperature because condensing temperature determines condensing pressure which, in turn, determines the generator pressure. In the idealized cases studied, we took the generator pressure to be equal to the condenser pressure.

Weil: Is there a limiting temperature differential between the generator and absorber?

Allen: Yes, at the point where the concentration of the stream coming out of the generator is equal to the concentration of the stream coming out of the absorber there is no possibility of obtaining refrigeration. At that point there is a temperature differential between the generator and the absorber.

Weil: In this connection, I didn't notice it on your graphs, but did you always assume that condenser and absorber temperatures are the same?

Allen: Yes.

Weil: Another question that was asked, related mostly to the lithium bromide-water system. In usual small lithium bromide-water systems, pumping is achieved without using a mechanical pump. Usually the pressure difference is maintained by a difference in liquid levels. Does this in any way enter into your calculation? Another related question is: Can the minimum cut-off temperature of a lithium bromide-water system be decreased if mechanical pumping is substituted for thermosyphon pumping?

Allen: Our claculations were based on an equilibrium (static) thermodynamic model of the vapor production process in the generator. This is equivalent to assuming a mechanical pump in the system. In the case where a vapor-lift pump is being employed, there is an additional generator temperature increment needed to meet the dynamic requirements of pumping. As the generator temperature is reduced, cycle calculations show that the refrigeration capacity for a given rate of solution pumping is reduced. Because of the additional temperature increment required with vapor-life pumping, the cycle would cut-off at a higher generator temperature than the cycle with a mechanical pump.

Weil: In the ammonia-water system that you analyzed, was any attempt made to optimize the utilization of the strong solution, the solution coming from the absorber, and how it was treated in the heat exchanger and the rectifier, or how it was used in the heat exchanger and the rectifier?

Allen: In the modified cycle calculations, we assumed the rectifier was cooled by the ambient temperature instead of assuming that the solution from the absorber passed through the rectifier heat exchanger.

Weil: My immediate reaction is that this would tend to give a lower COP by virtue of neglecting an optimization of the rectification. There are two people who asked this question and this implies that there is some question in minds of the audience. One felt that you did a first-law of thermodynamics analysis of the cycle and wondered why you didn't do a second-law analysis.

Allen: We were looking for reliable entropy data. When those data become available, we will complete the second-law analysis.

Weil: In a similar vein it was asked whether the collector should have its efficiency analyzed in terms of availability of the collected energy rather than just the energy itself. Here again one is presumably aiming at what you can do with energy that is limited by the second law as opposed to just considering it as energy.

Allen: In the work reported, we were concerned with analyzing irreversibilities in cycles with no heat-transfer temperature differences. We had not thought of analyzing the collector efficiency in terms of available energy until heat-transfer temperature differences were included throughout the combined collection-absorption system. One can evaluate the availability of collected energy as the different heat-transfer events occur during collection and delivery of heat to the absorption machine. In such an evaluation, the chosen environment temperature in the availability function would depend on whether one assumed dry-air cooling or evaporative cooling. In the absorption-refrigeration case, as with the Rankine cycle, it is certainly true that the available collected energy is inherently less than the earlier-mentioned useful heat output of the collector.

Weil: Well, I guess the significant in availability is a measure of the second law of thermodynamics whether it is a significant limitation in this case could possibly be the question.

Weil: Dr. Anderson, you have two questions here. The first one is, are absorbers other than lithium bromide now being considered for the solar heating application? The other one is regarding energy conservation and total energy consumed. The question is, what net economy is realized when one includes the real life, electrical energy demands of the absorption system accessories?

Anderson: That has been considered for many years. Any number of combinations have been looked at. There are some that have very good properties but we have a problem of what we're going to put them in. Many of them are rather corrosive. It would not help particularly with the lower temperatures that we have. They are primarily materials that would permit possible air cooling. For example, you might consider sodium hydroxide or sulfuric acid which would be a very good absorbtant, but we don't know what to put them in. Someone else has mentioned zinc bromide, lithium bromide and that's a very good combination, but again we don't know just what we'd put it in because it's on the acid side.

Weil: The other question had to do with the overall economy of an absorption cycle. The question was, real life electrical energy demands of the absorption system accessories.

Anderson: Now the figure that I gave this morning did not take in account the accessories. What I was giving was simply the input to the generator versus the output. Now we have to have some means of cooling it. Of course if you're using city water, running it into the sewer, which I'm sure no one would want to do, your power requirements would be very small. In the time when we produced these units, we also produced cooling towers that went with them. I think on the three ton unit we had a total consumption of about 800 watts. That includes the fan and the pump for the cooling tower. Now we're going to have a fan regardless of what equipment we use. We're going to have a fan on the evaporator to move the air. That's probably another 400 watts that you would have no matter what equipment you used.

Weil: Okay, those were the two written questions. I have two written questions for George Lof. He'd like you to comment on Gilman's presentation generally, but the specific question is, would you please speculate on a step by step buildup of the cost from solar panel material data already given to fully fabricated panel costs and to installed panel costs.

Lof: With regard to Stan Gilmans' presentation, I'm sorry I was out of the room when he answered a question which I raised on how will that system handle extreme cold conditions when there is no heat in storage. I presume electric resistance heating or auxiliary fuel supply will be used. You have a full capacity standby fuel supply? And now a general comment - I've always been disappointed in the idea of using a heat pump as a solar supplement simply because it cannot use the solar collector in the summertime. All that valuable solar energy is wasted during that part of the year when it is so abundant. The economics of solar heating are benefited by the application of cooling through increasing the load factor as Bill Beckman has pointed out. But I certainly think that efforts to develop a heat pump combination are in order, and I support them. I'm not optimistic about this system becoming the ultimate solution however.

On the other question concerning a step by step costing buildup on the solar collector, I'm not sure just what the question means. I assume that the question refers to the total cost of materials, the cost of their assembly and installation, now and in the future. I don't think we know enough about these costs to quantify all the items. I think we're going to have to deal in generalities at this point. As I have mentioned, the costs of the materials in the collector that we're building will be somewhere between \$1.50 and \$2.00 per square foot. The costs of labor may prove to be about equal to the materials costs, so the total could be about \$4.00. The collector is going to be built on the house roof, so this will be an installed cost. It allows nothing for profit, nothing for overhead or shipping. So, at the present time, a commercially manufactured collector might be priced at \$6.00 to \$7.00 per square foot cost. Again, I'd like to predict a fairly rapid descent to \$4.00, and with some of the advanced designs I've seen and the substitution for roof materials, I think the \$2.00 range is a possibility.

Weil: I think that concludes the written questions, so we'll turn it back to Charles Chen.

Chen: I'd like the questions from the floor.

Anonymous speaker: I thought I'd make one comment regarding Gilman's paper because I think this use of heat pumps to move heat around building may be very valuable to us, in the solar, heating and cooling field. Perhaps we don't all know that this originated just prior to World War II and was know as the WS Stair Patert for many years. WS Sair is one of the real old timers in the industry. He is still living about 91 or 92 and many of us must have known him. But, when that type of system was first promoted and looking back at the application data, you will note that it was tied to the changeover temperature of the building. The higher the changeover temperature, the more benefit one got from this type of system and it also used other sources. For instance, I can point to several hotels that used this system and used the laundry water for heat source, and also delivered heat when you wanted to get rid of it into the service water system. I'm sure we might be thinking of these complete systems, but let's be sure we do as we apply them.

Anonymous Question: Dr. Farber indicated earlier a range of COP values from .3 to .6 I believe, I wondered what the cooling water temperatures were that were used when those COP values were obtained.

Farber: We used shallow well water at 72 degrees.

Anonymous Question: I have a question for Dr. Allen. In the lithium bromide water system, when we speak of crystalization, is it lithium bromide that's crystalizing in the generator or not, where is it crystalizing?

Answer by Gene Whitlow, Whirlpool: The lithium bromide crystalizes, actually it's a hydrate and the crystalization takes place primarily in the heat exchanger and simple blocks the heat heat exchanger.

Don Spencer, University of Iowa: I'd like to ask a question of Lof. It has to do with the heating of the house even though this session deals with cooling. In Iowa, we often have our clear days in the wintertime when we want solar heat most after a storm which might leave a layer of ice or snow on the solar collector. Has there been any thought given to techniues for removing ice?

Lof: Not to my knowledge. This problem hasn't presented itself to me or my associated. I would comment that the snow problem is not difficult, because the snow is sufficiently transparent to solar radiation, that as soon as the sun comes out again after a collection of snow on the collector, a thin layer melts near the glass and the snow slides off. I would suspect that something of the same sort would happen with the ice and that you wouldn't have to melt the whole ice layer for it to come off, but this is a speculation. While I'm up here I'd like to pose a question to perhaps Redfield Allen, Erich Farber and Phil Anderson. I've been a bit disappointed today in that we haven't had a more critical comparison of the ammonia system and the lithium bromide system in absorption cooling with solar energy. In view of the fact that the ammonia system requires much higher pressure and requires higher pumping power to circulate the absorbtant, and is not under most codes permitted to be installed inside the building, and still has thermodynamically, essentially the same performance capability that the lithium bromide system, why are we still working with ammonia system as a possible user of the solar heat source?

Farber: Well remember now, that most of the people that we're talking about using lithium bromide/ water, and also ammonia/water absorption systems operating 200 degrees F. Because we believe that we will have to work with temperatures below 200 degrees F, then you run up into concentrations with lithium bromide and water due to insufficient pumping which give you this crystalization problem, which you do not run into with ammonia water, and the pumping costs is not as great as most people think.

Anderson: Actually in the units that we're talking about we're running with more dilute concentrations and we don't expect any problem with crystalization. We're going away from the crystalization line instead of toward it. With regard to pump power, I think there is quite a difference if you're going to make a ratio comparison. For example, an ammonia unit might use say eight hundreths to a tenth of a horse power theoretically and a bromide unit might use say two thousands of a horse power. We're still talking about relatively small horse powers.

Chen: I understand Arkla's three ton lithium bromide unit was discontinued some years ago and recently has become a very good seller because of the advent of solar energy.

Anderson: I'd like to point out that these units were and still are, of course, water cooled. With the trend to air cooling, we supplanted those units with the aqua ammonia which operates up around 350, 360 degrees F. It's an air cooled unit. These units are made only in the smaller tonnage, three, four, and five tons.

Anonymous Comments: Two comments one regarding that buildup of ice and snow in a solar house roof. We had that experience this past winter at the Delaware house. The solution was that the collector had to have a flush flat surface. Any projection tended to retain the ice and snow buildup. We have in the Delware house some nuts sticking out from the roof, the way the surfaces retain on the roof, so we came to the conclusion that we have to mount the collector in some other way that there will be no nuts sticking out from the roof so that snow and ice can melt down. The second comment is regarding a cooling system. I asserted that point earlier in another session, but I will tned to disagree particularly with Dr. Anderson regarding some other systems, lithium bromide base systems. We had a proposal to NAS in which we are proposing a lithium bromide, zinc bromide, mechanical system. Now this has good advantages compared to the lithium bromide water system and I'd like to mention a few of those here. One of them is that the crystalization is not much of a problem with the lithium bromide, zinc bromide, mechanical system compared to the lithium bromide water system. The lithium bromide, zinc bromide, mechanical system is less viscous than the other and lithium bromide, zinc bromide, mechanical system has a larger pressure drop in the system so the system does not have to be designed very carefully. The solar duty of the lithium bromide, zinc bromide with mechanical is slightly better than the lithium bromide water system and furthermore of course, you can go below zero temperatures so that you are not confined to temperatures greater than 32 F. There are other advantages. Now as for the disadvantages that Dr. Anderson has been asserting regarding the corrosiveness, this should also be dealt with but we should not close our eyes, to the possibility of the system that he proposed.

Answer: I didn't mean to respond to the last part of his question or answer it but to the first one. Before I moved to Florida, we obviously don't have any icing problems with collectors, I was at the University of Wisconsin, and there we had some problems when I worked with collectors. However, they were not very serious because the angle of inclination is so high that most of the time it slides off. Since you use a collector and you have some storage, you can always circulate some of that hot stored water through the collector, warm it up a little bit and whatever is on the collector surface will slide off.

SESSION IV - NEW TECHNOLOGY

Session Chairman: Harold Horowitz

SOLAR DESICCANT SYSTEM ANALYSIS AND MATERIALS

Peter Lunde

The Center for the Environment and Man, Inc.

The Desiccant Cooling System

I would like to talk about desiccant performance in solar air conditioning systems. A desiccant system is basically different from the other cooling systems. Figure 1 shows the basic adsorption air conditioning cycle using a desiccant. The room air is drawn into the air conditioning system where a regenerative heat exchanger heats the air to perhaps 100 degrees F. The room air, which is wet to a 55 degree dewpoint, contacts the adsorbing desiccant material where the water is drawn out of the air in an exothermic process. The heat is transferred to the outside and the air comes out of the adsorbing bed at 110 degrees F. That is a fairly warm temperature to go back into the room. We have the regenerative heat exchanger to transfer some of the heat back to the incoming air. If we put water into the air with a humidifier we then get conditioned air, typically 60 degrees F., and we can carry out air conditioning.

This system has a number of advantages for use in a solar powered cycle. We can use solar heat to carry out the desorption of the desiccant. When the desiccant gradually becomes saturated with water vapor, it is moved outside either physically (as for instance with a wheel) or by valving, and then hot air is blown through the bed to drive off the adsorbed water vapor. The desorption air is first heated (in the particular configuration of Fig. 1) by heat from the adsorption going on inside the conditioned space, and more heat is added from the solar collector. I have also shown some water storage which will let us operate the air conditioning system for more than the few hours a day that the sun favors the solar adsorber. Effluent gases from the desiccant are on the order 150 to 200 degrees F.

This is a relatively simple system. There are no pressurized gases involved, no high pressure liquids--most of the system is sheet metal. The COP's for this kind of system tend to be high--on the order of .7 and .8 if you do a thermodynamic cycle analysis. The system works well at 200 degrees F. and pretty well at 150 F., depending on the desiccant. It is not nearly as sensitive to the high-side temperature for instance as a lithium bromide adsorption system is. In fact, perhaps this system is the system of choice for a solar air conditioning applications. It tends to be a large system physically, but so do absorption systems. Absorption systems get smaller per ton of cooling as they get large. In the desiccant system the pounds of desiccant per ton of refrigeration tends to remain constant as you go up in size, so perhaps this is not the system for cooling a large building.

The Desiccant Dehumidification System

However, a large building can use this system for dehumidification alone. If you take the general system of Fig. 1, eliminate the humidifier and the regenerative heat exchanger, and then use it to dehumidify the make up air to a large building, it looks like a good system. If you have a lithium bromide absorption system installed, you can use air leaving the absorber to dry out the bed, and you can reduce the cooling load on a large building by up to 30%. You can take the latent load away with this system, and you can gain an additional advantage which would well be very important for a lithium bromide system: the ability to raise the low side temperature in that lithium bromide system, from the present 40 degrees (approximately) necessary for dehumidification, up to perhaps 60 degrees. So you can reduce the amount of lift in the lithium bromide system and that may well do a lot of good if it is a solar powered air conditioning installation.

The Humidification Step

Let us look at Fig. 2, which is concerned with the humidification step, not the desiccant dehumidification. If we hypothesize an infinite amount of air circulation within the air conditioned space, all we need for continued air is 75 F and 50% R.H. To get that using adiabatic humidification, we can start as high as about 115 degrees F. so there is no problem. However, if we want to use a realistic circulation of air, let us say 600 cubic feet per minute per ton of refrigeration, we can not start at 115 F. and get there by adiabatic humidification; rather we have to start lower, on the order of 95 degrees F. And that is why we had the regenerative heat exchanger in Fig. 1, to get the temperature down from 110 F. We could not humidify to the required temperature from 110 F. but we can from 85 F. Furthermore, of course the exchanger reduces the air conditioning load considerably.

Choice of Desiccant

Figure 3, from the ASHRAE handbook, shows some water vapor equilibrium curves for commonly used adsorbents. It shows the adsorption capacity of silica gel, molecular sieve, alumina gel and activated alumina. On a capacity basis, silica gel is the best performer from about 30% R.H. on up to 70% R.H. Molecular sieve is the best performer from zero to about 35% R.H. This is on a basis of total equilibrium capacity. Let me make an important point here. In the desiccant system, you are loading the bed with ordinary air from the kind of ambient we work in, 30% to 70% R.H. Silica gel is the system of choice, for equilibrium conditions. You do not always use equilibrium conditions, as I will point out later. At CEM we have investigated silica gel and produced the isotherms shown in Fig. 4. This is the most convenient way to look at the capacity of a desiccant. On the top you will see dewpoint, and on the left side you will see the weight percent of water that the silica gel can adsorb. The higher the dewpoint, the higher the equilibrium capacity. The isotherms that you see have been predicted from the nine data points noted on Fig. 4. We at CEM have a mathematical model which considers the physical chemistry of the adsorption of water on silica gel and is very consistent with a number of physical chemical principles, and it enables us to extrapolate with quite a degree of confidence as far as we have to the lower vapor pressures and higher temperatures you see here. The mathematical model is based on the concept (see Fig. 5) that there is a given amount of area XO on silica gel, and depending on the amount of water in the air that contacts that silica gel, a certain amount (the lower rectangular block) is adsorbed directly on this surface. The higher the water vapor partial pressure the more is adsorbed in the first monolayer. As the dewpoint of the air that it is in contact with goes up (the 3 drawings in Fig. 5 are for dewpoints of $-5^{o}F$, $20^{o}F$, and $60^{o}F$), not only does the amount of water that can be adsorbed in the first layer grow, but so does the amount of water adsorbed in a second layer and ultimately in a third layer, as shown by the other rectangular blocks in Fig. 5. That is the nature of the mathematical model which we have developed. Furthermore, this is not simply a steady state model, it is also a dynamic model which lets us predict the rate of the adsorption of the water on the silica gel.

Choice of Operating Conditions

Going back to the isotherms, we can display the desiccant cycle that I started out with as shown in Fig. 6. Beginning with the end of the desorption step, the adsorption bed is still rather warm (110 degrees F.) and we blow pre-heated air through it from the conditioned space starting at point A. The desiccant picks up water vapor until it finally becomes saturated with air at 50 degrees dewpoint and 90 degrees F. (point B). At that point it will have about 15% water vapor (by weight) adsorbed. Then the bed moves outside where it is heated by air to about 200 degees F. The outside air can be quite humid, having a dewpoint of perhaps 70 degrees F. and yet as far as the bed is concerned, it is dry, because its relative humidity is quite low at so high a temperature. Desorbing the bed brings us to point C where the amount of water remaining on the bed is about 2%. The bed is then cooled to about 110 F. and we begin again at point A. The net capacity is about 12.8%. The interesting thing is to notice how little the capacity changes if we had desorbed at say 150 degrees F. The residual water would then be about 5% instead of 2%, so we would drop from about 12 to maybe 10% net capacity. So we do not lose too much when the temperature from the solar heat source drops, and that is a very important point.

Well, presuming we have a 12.8% equilibrium capacity to look forward to, how much of that can we use? We would like to get that 12.8% every 5 minutes. Adsorb the bed for 5 minutes, desorb it for 5 minutes. This would give us a system you could put in my hands. It would be a very small system because as Fig. 7 shows, the shorter the half cycle time, the smaller the bed volume. The solid linear curve results from a preliminary analysis. If you consider the fact that it takes time to cool the bed off, you could never reach a zero cycle time and the dotted line would apply. The faster you can get the bed adsorbed and desorbed, the smaller your system is going to be.

But that is not the whole story. Figure 8 shows an adsorption time vs. loading curve conducted under the very most favorable conditions for silica gel. The upper curve is at a 60°F dewpoint, producing a bit higher capacity than the 12% I was just talking about. Note that it takes 90 minutes or so to come to equilibrium. You can not do any better than this at these conditions, so if we use a half cycle time of 10 minutes, we can get only half of the equilibrium capacity. I think in a real system, we would be tempted to do that. But you can not make these choices with an adsorption system unless you know your material. Knowing your material is very important. Otherwise, you will spend all kinds of time in the laboratory trying to optimize the cycle and you might miss.

Another important point is how are we going to arrange the bed? Adsorption systems ordinarily use a long bed as shown at the top left corner of Fig. 9. There is a zone where the adsorption takes place that moves through and finally out the end of the bed. You get an adsorption rate that falls off gradually (Fig. 9, top right) and then quits when the bed is saturated. There are some systems that you can run that way. I do not think you can run an air conditioning adsorption system that way. You are going to have a lot of material involved in a desiccant system and it is typically going to have a fairly high pressure drop. Pressure drop is likely to be a problem, and a long bed would have an especially high pressure drop. You would be tempted to turn the bed on its side (Fig. 9, bottom left) and if you could really whistle the air through, you could get an adsorption rate curve like that at the bottom right of Fig. 9. You would be tempted to stop adsorbing after one-third of the time shown and desorb it, to utilize the maximum adsorption rate. This would give a system where you were not working to the equilibrium capacity but you would be getting a smaller system for your trouble. The question is how short a bed is short? How do you quantify this? Again, the answer is know your desiccant material and have some fundamental knowledge of it, so that you can work these things out ahead of time and get the system optimized before you start on a long experimental program.

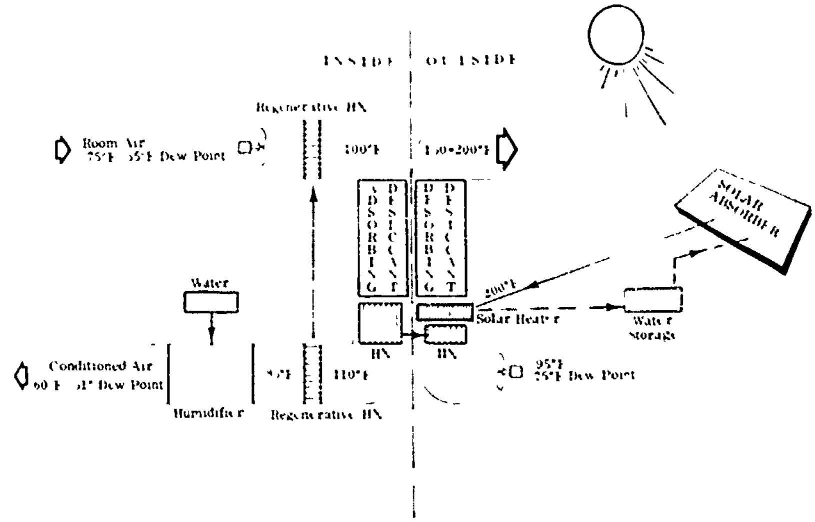


Fig. 1. Dessicant Solar Air Conditioning System.

Fig. 2. Psychometric chart for the humidification step. With infinite air circulation, dry air can be humidified from as high as 115°F to achieve room ambient conditions of 75°F, 50% r.h. (Line A). With a finite circulation rate, lower outlet temperatures are required. At 600 cfm/ton, the humidifier inlet temperature can be a maximum of 95°F (Line B).

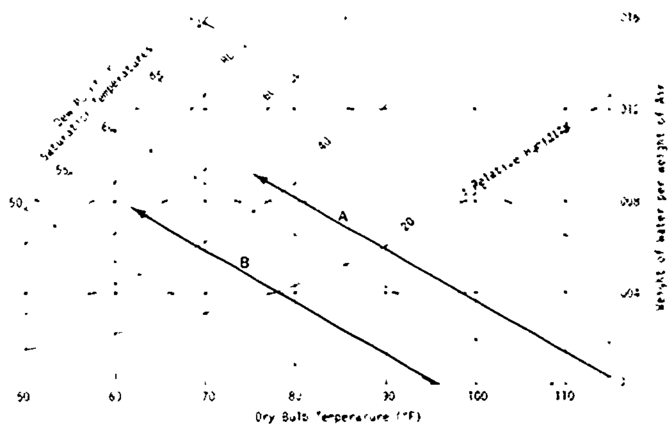
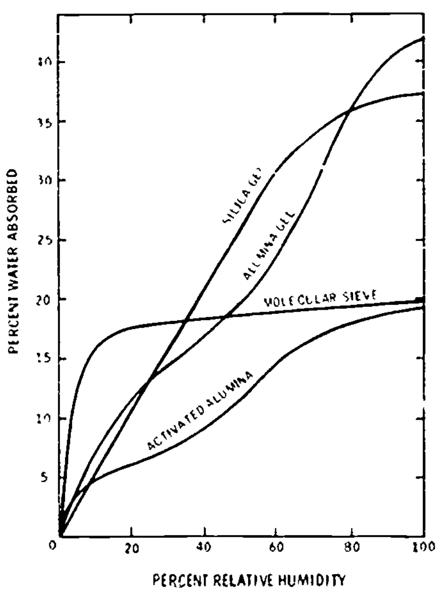


Fig. 3. Equilibrium capacities of common water adsorbents. Note the superiority of silica gel in the 30-70% r.h. range.



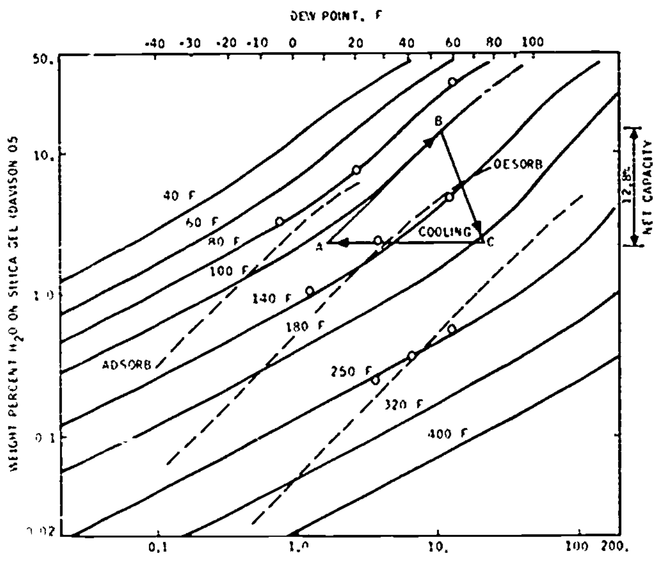
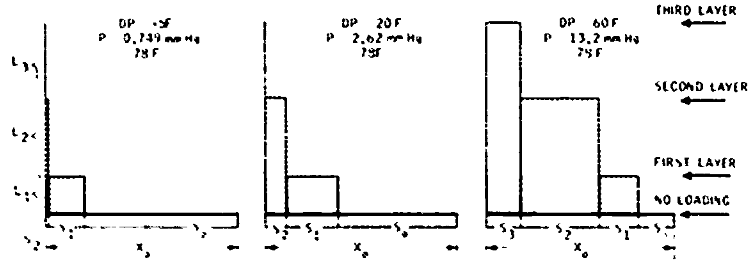


Fig. 4. Equilibrium adsorbtion isotherms for water adsorbtion on silica gel as predicted by the CEM adsorption model.

Fig. 5. Site concentrations and layer loadings predicted by CEM adsorption model at three dew points. The basic surface area (X_0) is occupied with layers of water which build up as the partial pressure of water vapor increases.



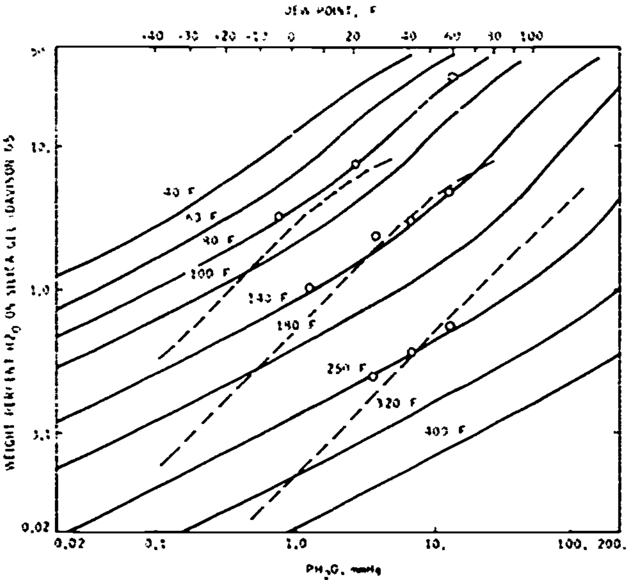


Fig. 6. A typical desiccant air conditioning cycle superimposed on the equilibrium isotherms of Fig. 4.

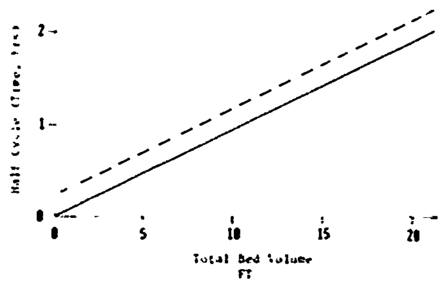


Fig. 7. The more rapidly the bed can be adsorbed and desorbed, the smaller it can be. The dotted line postulates finite heating and cooling times which limit the half-cycle time to a 15 minute minimum.

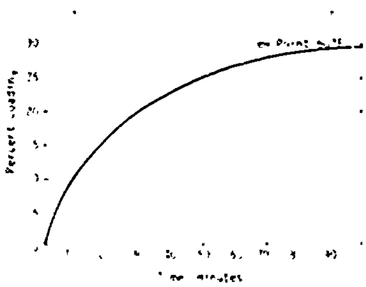


Fig. 8. This laboratory data shows how the rate of adsorption decreases as silica gel adsorbs water vapor. A practical system might get only 50% of the equilibrium capacity if the adsorption were limited to the first 20 minutes, when the adsorption rate is highest.

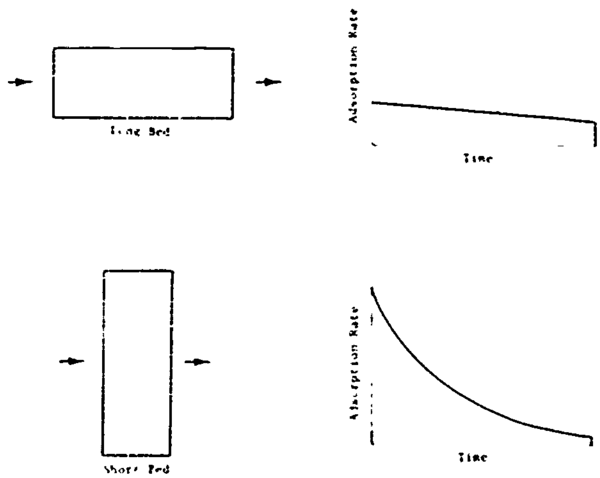


Fig. 9. A long bed has a slow but steady adsorption rate. A short bed has a high initial adsorption rate which rapidly decays.

A RETROFITTABLE SOLAR DEHUMIDIFIER

Sean Wellesley-Miller

M.I.T.

I would like to preface my discussion of our solar dehumidifier design with a few generalized remarks. Firstly, with regard to the thermal performance of buildings and secondly with respect to particular building types and regional climates.

When talking about solar air-conditioning we should remember that the demand for air-conditioning has been inflated by some rather poor architectural design in the past. Most of the existing building stock was designed on the assumption that energy would always be cheap and plentiful. Energy conservation was not a major design issue. The attitude was, and is, reinforced by the financial structure of the building market which emphasizes minimizing first costs rather than life-cycle costs.

Careful climatic design of new buildings could reduce the demand for air-conditioning dramatically, making it unnecessary in many cases. For example, Victor Olgyay (1967) has shown that optimized climatic building design would reduce the seasonal heating load of an average house in the New York area by 50 and the cooling load by as much as 70%. The life-cycle cost trade-off between investing more money in the building envelope or investing it in a more powerful space-conditioning system is definitely in favor of increasing the thermal performance of the building at the design and construction stage as Moyers (1971) and others have shown. Ideally the building and its cooling system should be designed together in terms of the local climate.

Givoni (1967) of the Building Research Institute in Haifa has published some interesting data showing the range of climatic conditions under which a properly designed building should require no mechanical air-conditioning at all. The area in Figure 1 on the chart bounded by the line N is the natural comfort zone. Boundaries M, V and EC show extensions of the comfort area achieved by mass ventilation and evaporative cooling. Primes show the allowable swings. Above and to the right of the composite area defined by these boundaries some form of mechanical cooling is required. Similarly to the left of the H lines heating is required.

As can be seen, the range of climatic conditions which can be handled by good building design alone is surprisingly large. In essence, the building acts as a buffer between the vagaries of the external climate and the space-conditioning system. When the air-conditioning system is solar powered an even more intimate coupling between the building and cooling system is possible. Benefits are:

1) A significant shortening of the seasonal and diurnal periods during which space-cooling is necessary.
2) An over-all reduction in the magnitude of the cooling load that has to be handled mechanically.
3) A leveling of the diurnal space-conditioning load profile.

Points 2 and 3 lead directly to a reduction in collector areas and heat storage capacity required and an attendant increase in the equipment utilization factor during operation.

A similar situation exists when it comes to the design of the solar cooling system to serve the building. The temptation is to go for a "brute force" solution that will be capable of serving all building types under all climatic conditions. Yet, if we do find such a generalized solution, which is still in doubt, it will almost certainly be as excessively expensive as its mechanical predecessors were excessively energy consuming. Personally, I believe that if solar cooling is to be genuinely successful we will have to develop and use a variety of technical approaches depending on local climate and building type. There is a real need for more research on the compatibility of generic solar cooling schemes with the characteristics of different climatic areas and building types. There is a tremendous difference between a single family residence and an 18-story office building. This difference is compounded if the office is located in Albuquerque, New Mexico and the house in Orlando, Florida. It is further amplified if the office is still on the drawing board and the home already in existence. It is doubtful if the same system would be able to meet both situations equally efficiently and economically. Solar cooling approaches based on night-sky radiation, evaporative cooling, natural ventilation, dehumidification, Rankine and absorption cycles or thermoelectric cooling are probably only marginally in competition given the range of climatic conditions in the U.S. and the variety of building types to be served. It seems to me that by prematurely insisting on a solar cooling system that can be neatly packaged into a mass-produceable product to be marketed nationally we may be in danger of pre-empting some potentially fruitful approaches to the basic problem of reducing national energy consumption by developing and substituting efficient and economical solar cooling systems for electrical air-conditioning.

The Psychometric Cycle

In designing our proposed system we were aiming for:

1) Low-rise residential construction.
2) A market defined by, but not necessarily limited to, the North Atlantic seaboard or the Boston to Washington "megalopolis." This region is characterized by high relative humidity and low day-to-night temperature swings.
3) Existing as well as new construction.

After considering a number of solar cooling schemes including an intermittent absorption cycle using liquid ammonia and sodium thiocyanate in combination with a two-step Fresnel lens collector we settled on a psychrometric cycle (Bullock and Threlkeld, 1966; Mullick and Gupta, 1973, Foster Miller Associates, 1973) as the basis for our design.

In essence, the device is a self-contained package that contains solar heat collector elements, absorption-desorption elements, and multiple heat-exchange sheets. This configuration offers the potential for the use of low cost materials and simple factory assembly, yielding low per square foot unit cost. In a typical installation, a suitable number of unit modules are mounted on the roof of a house, and household air is circulated to and from it in ducts, say in the attic "crawl space." In addition, a small storage tank and circulating pump is required for the liquid absorbent solution. This can be mounted in the solar package. Control is simple on-off of power to the pump and fan. The required heat rejection from the solar unit is obtained from natural convection (amplified by an integral "chimney" in the panel) and radiation to the ambient.

The fundamental advantage of this solar absorption de-humidifier over other air conditioning methods is seen to be that it is simple in construction and operation for very long useful life, and that it requires a minimum of solar collection area. Since humidity transport into a building is limited only by air changes while thermal transport is much harder to reduce, de-humidifying uses only a fraction of the energy that is used for cooling to produce an equivalent comfort level. Where humidity is required for comfort, a water spray turns the unit into a cooler. However, it is recognized that optimal design must be considered in the very broadest sense -- being the balance of first cost versus the sensible increase in human comfort in a typical house and climate.

Figure 2 is a schematic drawing of the cross-section of the unit. The structural layers of the "sandwich" package, named from top to bottom, are as follows:

1. Clear teflon film (or films) for the solar window, water collection, and heat rejection;
2. Felt coated, fiber re-enforced plastic corrugated sheet for solar heat absorption and flow distribution of the desorbing dessicant;
3. Glass wool insulation for trapping the solar heat in the desorbing dessicant;
4. A teflon film to isolate the desorption above from the absorption below;
5. Felt coated fiber re-enforced plastic corrugated sheet for flow distribution of the absorbing dessicant and for heat rejection;
6. A teflon film structural sheet for isolation of outside cooling air from household air;
7. Several simple layers of glass wool insulation and teflon film structure to exchange heat between the influent and the effluent household air while isolating it from the ambient temperature;

This structure provides all the functions of a high-efficiency solar absorption de-humidifier. A good absorber-desorber humidity transport medium is a liquid dessicant such as aqueous calcium chloride solution.

The basic cycles of the de-humidifier are:

1. Calcium chloride solution is exposed to indoor air to capture its humidity;
2. It is then heated by sunlight to drive off moisture;
3. The heat of solution of 1. is expelled to outside air.
4. Since 1. takes place above room temperature, it is thermally isolated from the building by passing the building air through a regenerator before it enters the dehumidifier.
5. A regenerator is also used for the dessicant solution to thermally isolate steps 1. and 2.

The unit operates as follows: Sunlight passes through the teflon film and turns to heat on the black felt. This drives water out of the calcium chloride solution as it drips down the corrugated fiberglass to the trough where it is collected. The water vapor condenses on the back of the teflon film which is cooled by ambient natural convection. and is collected in a trough. The concentrated calcium chloride solution is pumped through a counterflow regenerator (simply two tubes soldered together) and to the top of the second corrugated sheet, which it drips down. Air from the room passes over it and gives up its moisture. The heat from this reaction is rejected to the outside air in the cooling chimney. The room air then passes through an air-to-air counterflow regenerator, where it is dropped to room temperature before being expelled back into the room.

The cost of materials, excluding pumps, fans and the external box-frame is $1.50 - $2.00 per square foot for the entire system, which is comparable to materials costs for the collector alone in conventional solar air conditioning systems. This shows the advantages of a low energy density cycle and sandwich type construction.

A number of market considerations determined the details of the proposed design configuration. These included:

1. That the system can be retro-fitted to existing buildings as well as incorporated in new ones.
   a. Humidity transport into a building is limited only by air changes. Thermal transmission through walls and windows is much harder to reduce than air infiltration rates, especially in old construction.
   b. Humidity systems require less collector area for the same degree of subjective thermal comfort as absorption or Rankine cycle systems in most of the climatic area under consideration. 250 to 400 sq. ft. of collector would be a typical figure.
   c. The existing U.S. building stock is around 70 million. There are about two million new building starts a year. Due to demographic trends caused by the post-war baby boom new construction is likely to peak in the mid seventies and to fall off sharply in the mid '80's. Thus any system capable of making a major long term impact on electrical energy consumption by air-conditioning units must be retrofittable.
2. That comfort conditioning can be provided "on demand."
   This implies thermal storage since peak demand in this climatic area occurs during hot, "muggy", overcast periods. I.E., solar availability and cooling demand are not in phase during peak demand periods. This requirement can be met by storing the dehydrated salt in an inch deep pan at the bottom of the sandwich panel assembly (not shown in Figure. 2). Since the heat of hydration is higher than the heat of fusion one inch per sq. ft. gives 3 day storage. Both cooling and storage can be added to the basic unit as options.
3. That the system is compatible with solar heating.
   At present the proposed system does not meet this requirement. However, with some modification it might be possible to make it compatible with a hot-air system. The relatively small collector area required tends to de-emphasize this requirement, and avoids the complication caused by the different "tilt" angles required for efficient summer/winter solar collection.

4. Mass-produceable, modular construction.
   a) Retrofitting requires a modular approach to ensure fit with any existing buildings.
   b) Low tooling up costs requires the use of existing off-the-shelf materials and production techniques. There is a complex trade-off between operating temperature, collector area and materials costs (e.g., plastics).
   c) Economic marketing and transportation require high value to volume and value to weight ratios. Vibration and impact strength has to be designed to military specifications to avoid breakage.
5. Easy handling and maintenance
   a) The potential market is increased if maintenance servicing is simple and requires little or no special training. This calls for corrosion and weather resistant materials such as teflon (F.E.P.).
   b) A "kit" form that could be assembled and installed by home-owner would avoid the high costs of plumbing labor. (20% of new single family homes are owner built). This implies that the modules should be light, less than 100 lbs; of simple construction, 1 by 4 by 8 ft. sandwich panels and of an easy to handle geometric configuration. The modules are self-aligning, assembly consists of plugging them together, taking the air in and out of the house and providing electrical power for the fans and pumps. No other equipment should be required.
6. Reliability, safety and controls
   In order to achieve a high degree of market acceptability, the system must be reliable, safe and simple to control. To be compatible with the average life-time of a typical roof the system should have a life of 30 years. Moving parts should be minimized. Safety and simplicity of controls favors the diffuse, low energy density approach. Calcium chloride solution is non-toxic, non-corosive and non-flammable.
7. Costs
   a) Electrical utility rates are expected to rise by between 7 and 10% a year. The system is estimated to cost about $2.50 a sq. ft. systems costs and to pay for itself in 10 to 15 years and to last 20 to 30.
   b) The current market saturation level of air conditioning units suggests that air-conditioning in the residential market is still something of a luxury. A cheap system that worked well most of the time would be attractive to many people. Thermal storage and sensible cooling capacity are available as options.

These design requirements are presented because they are probably relevant to most solar cooling designs. However, the proof of the pudding is in the eating. We hope to construct and test a prototype of this system under an NSF/RANN grant. (Foster Miller Associates, 1973) If this occurs I will then be able to give you more concise data on operating temperatures, C.O.P. and other performance data.

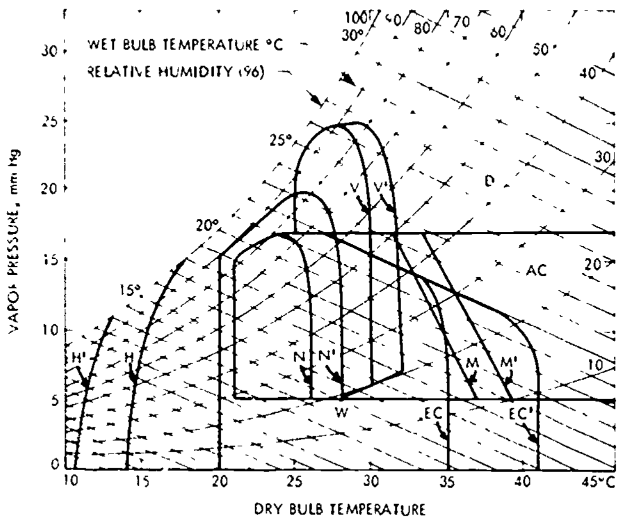


Fig. 1. Climatic Conditions Needed for no Air Conditioning Requirements.

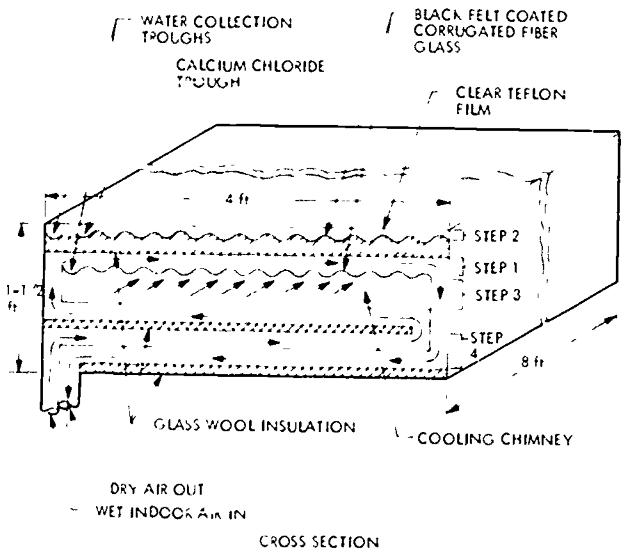


Fig. 2. Solar Dehumidifier.

SOLAR DESICCANT SYSTEMS

William Rush

Institute of Gas Technology

We were charged with the assignment of building a dessicating-type comfort system about four or five years ago. This work was sponsored by a very hard nosed group of people, namely, the gas industry. The objective was to build a device that in the cooling mode would be as efficient as a compressor system. The heating mode had to be at least as efficient as a gas fired system. It had to be priced within 20. of the price of the combination. Further, it had to be able to heat, cool, humidify, dehumidify, and ventilate, and it had to use minimal auxiliary power. We came out with a device that worked very well for a short period of time until its performance deteriorated, forcing us back to the drawing board.

For the best understanding of the operation of the unit, one should understand how it works as a gas fired device only. I'm going to concentrate on the cooling mode, and then we will show you how solar energy fits in. Figure 1 shows the Munters Environmental Control Unit, which I will call the MEC unit. The Munters Corp. located in Stockholm, was founded by the same Carl Munters of the Munters-Platen absorption system. Munters Corp. was responsible for the early development of this idea.

First, concentrate on the stream marked outside air "in" and assume that the air is about 95 degrees and 75 degrees wet bulb. It passes through a drying wheel made up of a series of corrugations in which a desiccant is contained. The stream goes through an adiabatic dehumidification step, where it is dried to less than 0.003 pounds of water per pound of air reaching a temperature of about 180 degrees F. As Lunde showed earlier, this sensible heat must be removed. The hot, dry air then passes through a heat exchanger wheel, where it stores its sensible energy. It comes out off the heat exchange wheel at about 80 degrees F, but it's still bone dry. What we have done so far is given everybody in the whole country Yellott's Arizona climate. We then humidify this air and deliver a conditioned air stream at about 56 degrees and almost saturated, which is very similar to what one obtains from a conventional air conditioning coil today. On the other side, room air is shown entering. Normally, this might be about 75 degrees dry bulb and probably about 63 degree wet bulb. With its potential of being cooled by saturation to 63 degrees, it becomes the heat sink for removal of the sensible energy that was stored on the other side by the conditioned air stream. Now we put in a gas burner. We heat the regenerating air stream to the temperature that is sufficiently high to drive the water off that was absorbed on the other side. The vapor is rejected to the outside.

You will notice we have a completely ventilated system. It delivers 100% fresh air to the room while room air is continually exhausted. Actually, we have not been operating the unit in this mode. Figure 2 is a schematic of what the present operating mode looks like. Instead of having the air come entirely from the outside, it is shown as operating in a recirculating mode. This is the normal way an electric air conditioner operates in which air circulates from inside the conditioned space to where it passes over a coil and delivered back to the room. The conditions indicated are ARI standard conditions,-an 80 degree room with a 67 degree wet bulb.

It goes through the drying wheel, comes out "bone" dry, at about 180 degrees F. Again, the sensible heat is stored in a sensible heat exchanger, where the air leaves at 80 degrees F. After saturation, it comes out at 56.5 degrees dry bulb and 53 degrees wet bulb. The ambient is again shown at ARI standard conditions of 95 degrees and 75 degree wet bulb. So, theoretically if this ambient air passes through its own water curtain it can reach a temperature approaching 75 degrees. This stream becomes the heat sink as it passes through the heat exchange wheel and it approaches 180 degrees. A gas burner, shown as a quadrant burner, provides regeneration by allowing half of the gas to preheat the drying wheel while heating the other half to a temperature sufficiently high to dry the wheel.

Figure 3 shows actual operating data. You will notice that the cooling effect on this particular unit happens to be 2.7 tons. The COP is 0.73. Because of hardware shortcomings, I believe that the actual COP is closer to 0.8. The 0.73 results by taking the enthalpy difference between the inlet and outlet conditions and multiplying by the flow rate. Actually, we were probably handling about 10 percent more air flow than indicated. We had some peripheral leaks, and we didn't know how to solve them at that time. So, one would actually be multiplying the measured difference in enthalpy by an air flow that is 10 percent higher-making the COP about 0.8.

Figure 4 shows the performance at part load conditions while the COP remains at 0.71. The gas input was 24,000 BTU per hour which is about 24.4 cubic feet of gas. Therefore this is a COP based upon the actual flow of gas and is not a net but a gross value.

Figure 5 is a schematic of the solar energy system. It shows the solar MEC unit as well as the solar collector and storage. Storage is very important. It is very desirable that you run 24 hours a day if you possibly can on an even load to eliminate peaking. If all of a sudden at two o'clock in the morning one runs out of stored energy, the gas company is not going to be the least bit enthused by the fact that everybody demands fuel at the same time. So, peaking is a very important factor.

Figure 6 is taken from a NASA Marshall Space Flight Center publications. We based our design on the collector performance curve for the indicated selective surface. This curve shows about 50 percent collection efficiency at 250 degrees. We designed to collect and store at 230^{0}. In the upper part of Figure 7 one sees the regenerative side of the gas-fired unit. The air from the outside went through the evaporative cooling pad and was cooled to about 80^{0}F. It became the heat sink as it passed through the heat exchanger being heated to 176^{0}F. Notice again that it is a quadrant burner. It heats just the upper quadrant. So, the lower stream preheats the drying wheel to a maximum of about 176^{0}F. The upper portion passes over the burner and is heated to a maximum temperature of 290^{0}F. It's a topping temperature that must be reached and designed for. Observe what occurs with a 230 degree storage temperature. We designed to take a 10 degree drop in the solar coil and return to storage at about 220^{0}F. This heat exchange coil was designed for a 5 degree approach so the heated stream leaves at 225^{0}F. (Some may feel this is too close a temperature approach and that 8^{0} is more reasonable). The designed heat exchanger fits nicely into the available space. Now observe what happens in the lower part of the figure. If one has 225 degrees (or some temperature close to it), one is now able to heat the drying wheel well above the boiling point of water as it passes over the preheat section. This allows for using a great deal more of the arc than one formerly could with only the 176^{0}F air when on gas-firing only. This means that a full quadrant burner is no longer required.

Notice that the air stream passing over the burner has also been heated to 225°F. Heating this stream to the final temperature of 290°F benefits us in two ways. First, more thermal energy entered in the lower part of the machine than formerly. Second, only one half of the air is heated over half the difference. The net effect is that if this system, operating as a gas unit, would require 100 cubic feet of gas per hour, the introduction of a solar coil would reduce gas consumption to about 20 percent-20 cubic feet per hour.

Figure 8 shows the solar MEC unit operations in the heating mode. Only the drying wheel is shown. This is because in the heating mode the sensible heat wheel is not needed. To give you a feel for size and speeds, the box is a cube 40" x 40" x 40". The drying wheel, in the cooling mode, is rotating at one revolution per 5 minutes. In the heating mode it goes about 4 to 5 revolutions per minute. In the heating mode the drying wheel loses part of its desiccating ability at this increased speed-but it becomes a better heat exchange wheel. Incidentally, Figure 8 shows the heating operation in the ventilating mode. Conversations with manufacturers indicate they are reluctant to install the internal ducting so that one can alternate between a circulating mode for cooling, and the ventilating mode for heating. We shall have to choose to go one way or the other. However, if one can reject the air and use 100 percent ventilation, one is better off. Let me show you why. Because the drying wheel is now a very good heat exchange wheel, one can take all of the room air and pass it over the solar coil. If we were storing at 230°, we don't want to deliver air that temperature. In fact, we chose to reduce part of the heat exchange surface for heating so as to leave at 128 degrees F. This was done deliberately. By using the indicated amount of gas to heat to 179 degrees F, this allows us to use all of the stored energy over a 24 hour period when operating at design conditions of 0 degrees F. Notice the energy saved when you can reject combustion products to the outside at 16 degrees F. instead of at the temperature you are currently rejecting such products to the outside in today's chimneys.

Although the wheel at this increased rotation has become a good heat exchanger, it is still a fair desiccant wheel. Therefore, a significant part of the latent energy that ordinarily would have gone up the stack is also retained on exit side and is transferred to the side handling the air returning to the room. On this design basis, which is a 0 degree day, we would be putting in a net of 673 BTU's per minute while delivering to the room 1167 BTU's per minute. The indicated burner is a 100,000 BTU burner. A 100,000 BTU gas burner has 70,000 BTU's useful net energy in it so one would be able to meet all of the heating demands on this particular day. If you select a typical heat gain characteristic for a building such as for the one that was in the NASA Marshall report, you will find that at about 35 degrees F. and above, you are completely independent of any auxiliary gas.

The unit you have seen is the result of about seven years of intensive study at IGT. All the functions of heat transfer and the thermodynamics and kinetics associated with the drying step have been analyzed. A computer model simulating performance under a variety of conditions was developed and used as the basis for the selected design. In other words, the embodiment shown and discussed represents a device that we believe ready for field testing and well beyond the research stage.

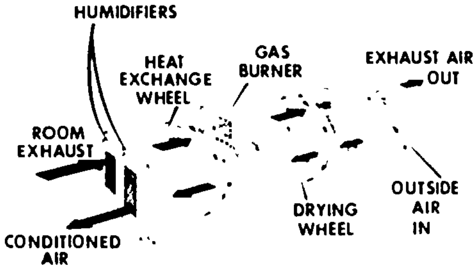


Fig. 1. HOW MEC WORKS "Ventilating Mode".

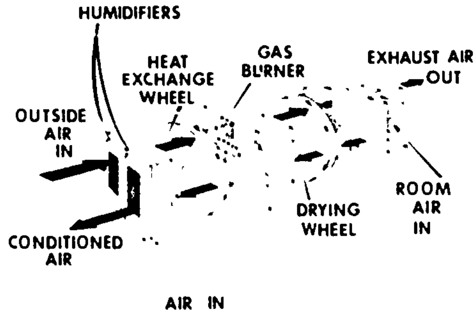


Fig. 2. HOW MEC WORKS "Recirculating Mode".

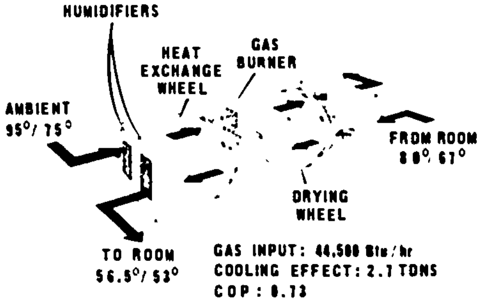


Fig. 3. Mec Unit, Recirculating Mode, ARI Conditions, All Flows: 56.1 lb/min.

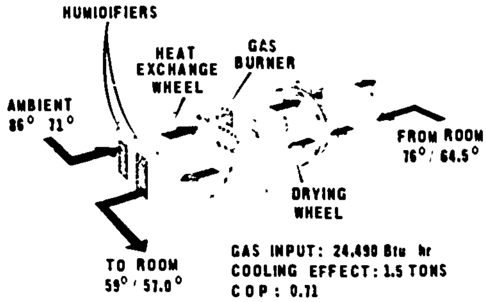


Fig. 4. Mec Unit, Recirculating Mode, "Part Load" Conditions, All Flows: 55.3 lb/min.

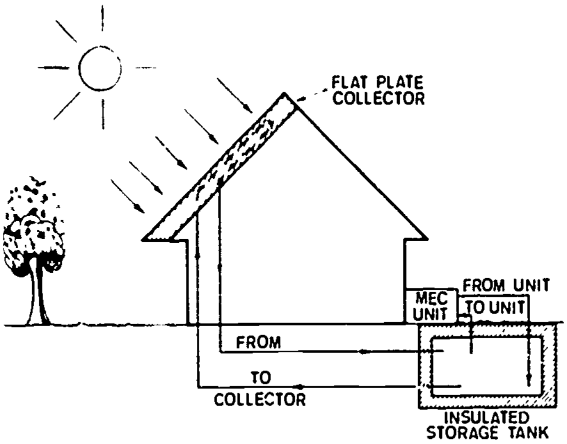


Fig. 5. Solar Cooled House.

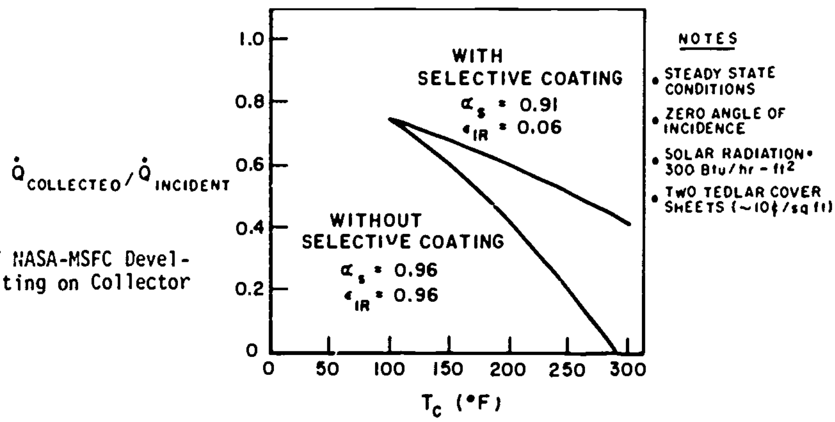


Fig. 6. Effect of NASA-MSFC Developed Selective Coating on Collector Efficiency.

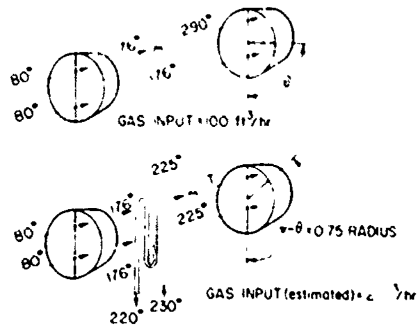


Fig. 7. Non-Solar VS Solar Mec Embodiments.

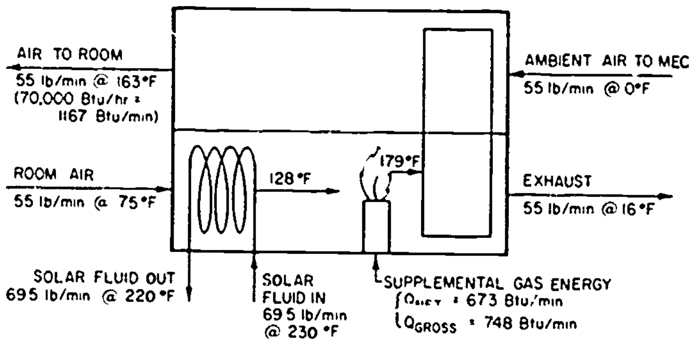


Fig. 8. Heating Mode Operation of Mec Unit.

A SOLAR VUILLEUMIER SYSTEM

Benjamin Shelpuk

R.C.A.

The ideas I am going to discuss this evening are not based on new principles. The concept of regenerative gas cycle engines was proposed as early as 1816 by Rev. Robert Stirling who applied for a patent on a machine which operated on principles similar to those which I shall discuss. The thermodynamic cycle which Stirling described is now known as the Stirling Cycle and was studied by most of us in our basic thermodynamics courses. The cycle consists of two isothermal processes, one of compression, one of expansion, and two processes of heat transfer in constant volume. Professor Gustav Schmidt (1871) published an analysis in which he obtained the work output by an integration step. This method has been adopted and is used to this day for most classical analyses of the Stirling Cycle and indeed is the basic method which we have used to generate the results which I will discuss this evening.

The system which I am discussing tonight is actually a variation of the regenerative cycle originally proposed by Stirling and was described by two people early in this century. Rudolph Vuilleumier in 1910 filed for patent on a device which operated on a cycle which has since become known as the Vuilleumier cycle. Later in 1935 Dr. Vannevar Bush also filed for a patent on a similar kind of machine. The thermodynamic cycle presented by both Vuilleumier and Bush is illustrated on Figure 1. In a very real sense this cycle can be described as a combination of the classic Stirling heat engine and refrigeration cycle operating as interacting open cycles. Any given volume can no longer be treated as a closed volume since there is a mass crossing the boundary from the power volume into the cooling volume and vice versa. Thus the cycle thermodynamic analysis must be done on the basis of three interconnected open system control volumes. The compression and the expansion processes occur in steps 1 and 4 are in reality accomplished by boundary work being done by or on the control volumes as they expand and contract.

In the three cycle PV diagrams at the bottom of Figure 1 you can see what is happening conceptually in each of the volumes; step 1 to 2 is an isothermal compression while the gas is in the ambient space and thus the heat of compression can be rejected to the ambient heat sink. Steps 2 to 3 can be thought of as a constant volume process in which the gas is cooled as it passed through the regenerator and into the expanding cold volume space. Process 3 to 4 is an isothermal expansion of the gas in the cold volume space and then, of course, steps 4 to 1 is the constant volume heating process. Simultaneously, similar processes are occurring in the hot volume and in the the ambient space volume.

You will notice from the thermodynamic sign of the direction of the process that heat must be added in the cold volume and also in the hot volume and there is an excess of energy which must be rejected in the ambient space. The amount of refrigeration which occurs is a function of the pressure ratio between compression and expansion processes and the total swept volume of the cold cylinder. The thermodynamics of this cycle has been described mathematically and has been confirmed by experimental data taken on many models in the laboratory.

It is interesting to note that there have been many successful applications of this thermodynamic cycle. Stirling heat engines with 39% conversion efficiency have been built. Cryogenic refrigerators based on both the Stirling and VM cycles are common.

Figures 2 and 3 show two experimental Vuilleumier cycle refrigerators which have been built and tested at RCA. The first refrigerator is one which was built to show the feasibility of building a cooler which required no mechanical input at all. In this refrigerator the driving energy for the cycle is through a gas burner shown at the top of the machine and the movement of displacer which is usually done with a small electric motor was accomplished by building small pistons into appropriate areas of the machine so that the pressure pulse created during refrigeration cycle could be utilized to self-actuate the displacers. This refrigerator has a refrigeration capacity of 3 watts at $77^{O}K$ and operates from a fuel rate of less than 1/10 lb/hr of propane. The second refrigerator shown in Figure 3 is also based on the Vuilleumier cycle and in this one the purpose of the experiment was to show the feasibility of a linear motor electric drive for the displacer activation and also to show the capability for remote pneumatic actuation of the cold displacer device. The upper part of the device in the photograpn is the cold cylinder. It can be remotely located from the compressor which is located in the bottom half of the photograph. There is no mechanical linkage between the two as the actuation of the refrigerator is strictly by pneumatic means from the pressure pulse generated within the device. This experiment also was successful in producing refrigeration and is the construction concept which I would think would be applied to a device built for an air conditioning application.

The question which one can reasonably ask is, "Given this high level of success with regenerative cycle gas machines both as heating engines and as refrigerators, why has this device not been used in applications near room temperature?" If one examines the idealized equations of performance, it is clear that the efficiency of performance which would be expected is very high, even at temperatures near normal room temperature. However, when one gets into analyzing the regenerator and heat transfer problems that exist at this temperature, it is obvious that the performance required in these components of a machine is substantially different than that required in a heat engine or a cryogenic refrigerator. It is thus this unique regenerator design problem which has impeded the development of this kind of device for air conditioning applications. I think probably almost as important as that is the fact that the vapor compression cycle which has been developed for most air conditio ers has performed so well that there has not been a need to develop this concept for that application.

Max Jacob in his treatise on heat transfer in volume II says that the analysis of a regenerator is among the most difficult and involved tasks that can be encountered in the field of engineering. I think there is good reason for the technical community to address the very difficult regenerator problem for air conditioning applications. An air conditioner built on these principles would have many interesting features. First of all, high reliability can be expected because in the machines that I have described there are essentially only two moving parts, both the displacers. Bearing problems should be nominal because of light loading. Secondly, the refrigerator uses a safe refrigerant, helium. Thirdly, we have predicted that performance of a C.O.P. approaching one can be achieved when this refrigerator is driven from a solar energy source. A significant feature of this system is that it is a hermetic combination engine-refrigerator thus eliminating seal problems. In addition to all of those things, we also feel that low production costs can be achieved in this kind of refrigerator because we are not looking at any close tolerance of mechanical parts. Rather than belabor you with the details of the tasks which must be completed to develop the appropriate regenerator and heat transfer structures that would make this thermodynamic cycle applicable for air conditioning app .tions, I should like to quickly outline what is required and show you calculated performance characteristics based on concepts which we have developed for the critical regenerator and heat transfer structures needed.

First of all, it is important to realize that typical regenerator structures used in most machines are matrices and material such as spheres or screens or cut-up-wire which causes a high resistance to gas flow but provide a large surface area for heat transfer to the thermal storage medium. In the application for air conditioning our analysis shows that a typical machine would have to regenerate instantaneously at a rate of 1M BTUs/hr even though the net capacity of this machine is only 33,000 BTU/Hr. This can only be accomplished through structures which have low resistance to flow and yet have high thermal performance required of generators. In addition to these parameters, a minimum void volume must be contained in whatever regenerator structure is developed since its presence deteriorates performance in a very dramatic way.

Figure 4 shows a list of variables which are relevant to characterize regenerator performance. I direct your attention to the equation at the top of the Figure. This is the equation which gives the value of heat transfer per unit flow work in a regenerator, and of course, a good regenerator maximizes the value. You can see from the equation that there are three groupings of parameters that are involved. First there is the "J/F" factor which is descriptive of the type of regenerator or heat transfer structure being considered. The second parameter has to do with the gas that is being considered, and the third grouping has to do with the actual application temperature difference and the velocity of the gas flowing through. Now with regard to the gases, you can see in the table below the equation that the heat transferred per unit flow work is maximized as the atomic weight of the refrigerant gas goes down. This makes hydrogen better by a large factor than any of the other alternatives although helium is a good alternative. The J/F factor is another factor which has a wide range, ranging from .04 and .15 for the typical regenerator structures to a J/F of 1/2 for flow through parallel plates.

As I have indicated previously, based on our analysis of the required regenerator and heat transfer requirements for an air conditioning application we can describe a set of material, heat transfer and structural parameters which we feel will lead to good gas regenerator gas cycle performance in the air conditioning application.

Figure 5 shows a typical heat balance in the calculations that we have done thus far. Here you see the characteristic of the machine which we have investigated. It is operating with the heat source temperature at 350^{0}F, sink of 110^0, a refrigeration temperature of 35^{0}F and at a speed of 3 Hz. The gross refrigeration capacity that results from using all of the parameters that we have assumed is 42,000 BTUs, the losses as shown are subtracted from the gross capacity and the net refrigeration capacity is 33,000 BTUs or almost three tons.

In Figure 6 and 7 the performance of the solar driven refrigerator which we have analyzed using these methods is shown. From Figure 6 it is clear that the capacity and the C.O.P. are a strong function of heat source temperature. This curve is for a temperature in the cold space of 35^{0}F. This allows for ample heat transfer difference to maintain the cooling coil at somewhere between 40 and 45^{0}F. You'll notice that the C.O.P. for the 110^{0}F heat sink temperature range approaches 1. The C.O.P. goes up where the lower ambient temperature exists and is well above 1.2.

Figure 7 shows the same set of curves with a different temperature set, specifically the cold temperature is held at $45^{o}F$. You can see the effect of the heat transfer on the cold side of the air conditioner.

This discussion of necessity has been brief and has lacked detail in certain areas which might be of interest to some of you, but I think the essence of the conclusions that we have reached is that air conditioning can be accomplished by using a regenerative gas cycle which combines the elements of a heat engine and the refrigeration cycle. Performance which is at levels that would be required in a home application is feasible. I think the clear indication of what must be done to realize success in this area could be broken into three categories.

First of all, the preliminary analyses which have been completed and which have been shown here need to be more thoroughly explored with regard to regenerator and heat transfer structures which will give is the most desirable machine configuration in the 2 to 3 to 5 ton air conditioning range. This screening type of analysis I think has to be done using the simolified methods of the Schmidt relationships. Once the initial screening has been done and a system is characterized, I think it is important to use some of the more sophisticated analytical techniques such as have been described in the literature by Finkelstein (1960) regarding the Stirling type refrigerators and more recently by Alan Sherman (1971) at NASA in describing VM refrigerators.

And I think finally we need to verify experimentally the performance parameters that are predicted by these various techniques and to do experimental and design work to solve the problems of implementation in an economic and reliable fashion. I think that the promise is there for good performance under the conditions imposed by the solar energy application, and I think that this technology merits the interest and development work by all those who have something to offer in this area so I recommend it to you as a potential method for providing the air conditioning requirements in buildings from a solar energy source.

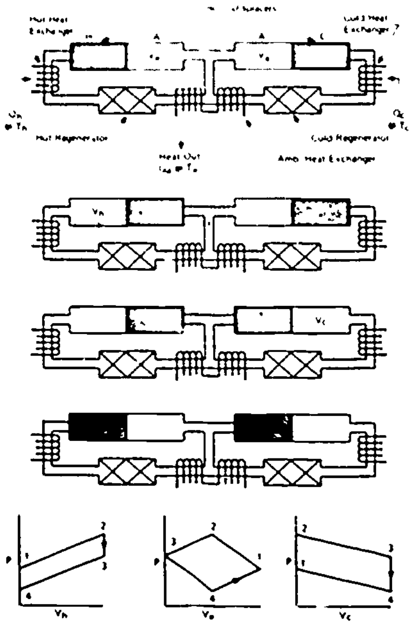


Fig. 1. Stepwise VM Cycle.

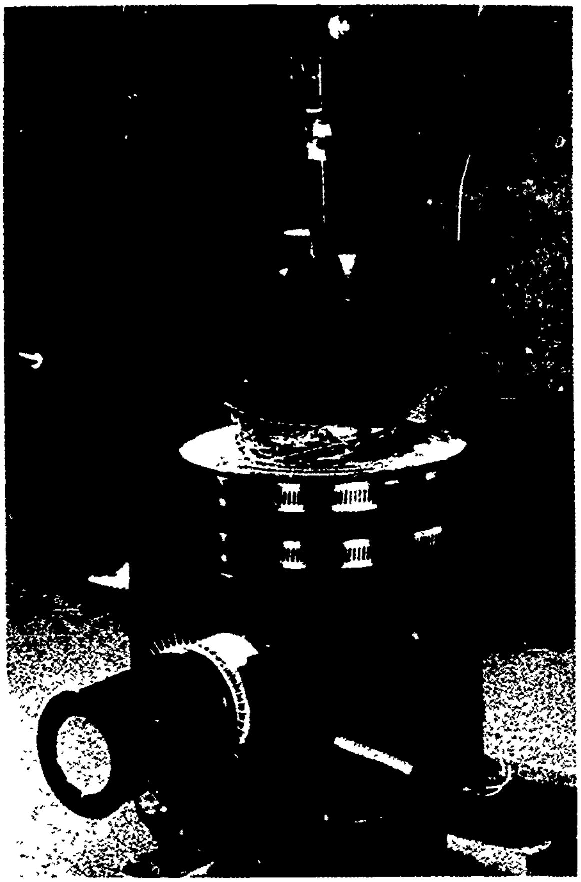


Fig. 2. Experimental VM Cycle Refrigerator Requiring No Mechanical Input.

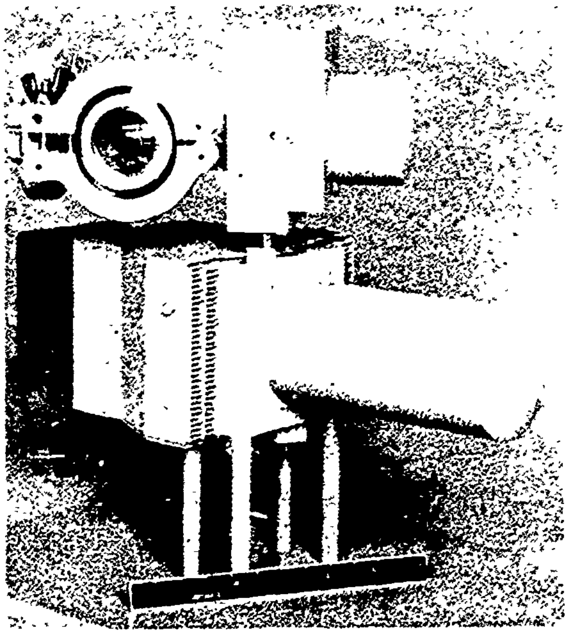


Fig. 3. Experimental VM Cycle Refrigerator with Mechanical Displacer Activation.

$$\frac{Q}{W} = \frac{1}{f}\left(\frac{2 C_p g_c J}{N_p^{2/3}}\right)\frac{\Delta T}{V^2}$$ HEAT TRANSFERRED PER FLOW WORK

Q/W FOR VARIOUS GASES

GAS	Q/W	(Q/W)/(Q/W) H_2
HYDROGEN	111 217	1.0
HELIUM	40 978	2.7
NITROGEN	7 949	14.0

ΔT = 1 F
V = 1 fps
N_p = 1/2

$\frac{1}{f}$ 15 WOVEN SCREENS

$\frac{1}{f}$ 04 SPHERE MATRIX

Fig. 4. Regenerator Flow Variables.

TOTAL GAS VOLUME	154 IN^3
VOID VOLUME	68 IN^3
PRESSURE	3500 PSIA
SPEED	8 Hz
HOT TEMPERATURE	350 F
HEAT SINK TEMPERATURE	110 F
REFRIGERATION TEMPERATURE	35 F
GROSS REFRIGERATION CAPACITY	42200 BTU/HR
REGENERATOR LOSSES	8090 BTU/HR
FLOW FRICTION	510 BTU/HR
NET REFRIGERATION CAPACITY	33600 BTU/HR

Fig. 5. Typical Heat Balance.

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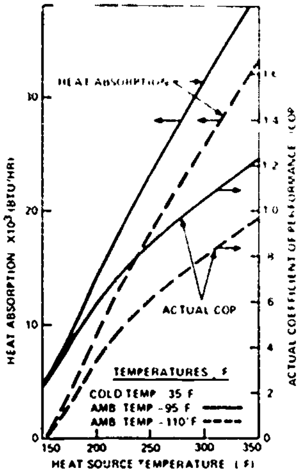


Fig. 6. VM Air Conditioner Performance Versus Fluid Temperature.

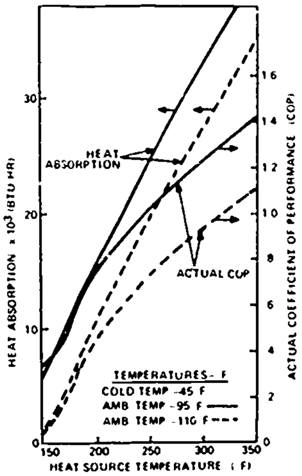


Fig. 7. VM Air Conditioner Performance Versus Fluid Temperature.

HOW TO STOP COOLING LOADS BEFORE THEY START

Harold R. Hay

Skytherm Proc. and Eng.

To stop cooling loads before they start is not beyond my intellectual level-it was practiced by primitive man and earlier animal life finding a suitable microclimate in a cave or under leaves or rocks. The most successful thermal control created by man is at the center of the pyramids of Egypt-giving the dead more thermal comfort than the living have outside. It has been estimated that it would cost over one billion dollars today to build the largest pyramid, hence even Mr. McCulloch is not apt to move one to Havasu City, Arizona, for erection alongside the London Bridge so we can more conveniently appreciate the thermal effect of building materials balancing the diurnal and seasonal thermal flux.

Geographic climatology is basic to stopping thermal loads before they start. If energy conservation becomes truly criticial, and many think it is that now, new federal buildings, and even some offices of states in which thermal loads are high, should be built in an area of the country where thermal loads are low - in the Southeast or Southwest where natural air conditioning can be based upon climate, building materials, and simple technology. The saving would be not only that energy consumption in the government buildings but also in the houses of the employees and of their supporting infrastructure.

Heating and cooling loads increase as buildings get higher; we are well advised not to go in that direction. Earlier man lived underground in all parts of the world; now the wish for more space in office buildings with above-ground height limited by city ordinances results in underground levels not only for garages but also for stores, banks, etc. - literally plazas have been pushed underground. Nathaniel Owings, whose firm is building the tallest skyscraper says that except for a few cities the skyscraper is a thing of the past. Constantine Doxiadis, the world famous planner, suggests two stories above ground and two underground for future buildings to regain the human scale. It could also stop heating and cooling loads before they start and keep them within the human scale.

At this workshop, some speakers advocate priority for solar cooling of high rise commercial and industrial structures with residential use receiving lowest priority. Politicians, more acutely aware of all the "heat loads" of such nonsocial recommendations, will disagree. It is no solution to add a $1000 solar collector onto a residential absorption cooling unit which will still require so much electric power to operate that even a medium income family might not be able to afford either the first cost or the operating cost. Instead of making such recommendations, technologists should stop political social heat loads before they start. In the vernacular, good advice to technologists would be; "cool it, politically."

Congress is passing legislation to support early commercialization of solar heating and cooling of residences and expects solar heating to be commercially advanced in three years and cooling in five. Congressmen exceeded the logic of some attending this workshop by starting with definitions such as "the term 'combined solar heating and cooling' ----includes cooling by means of nocturnal heat radiation, by evaporation, or by other methods of meeting peakload energy requirements at nonpeak load times;...." This does not require that solar energy be involved in the cooling.

Recognized in the definition, and in the timeframe by emphasis that solar heating and cooling should reach early commercialization within the 3-5 year periods and as soon as possible, is a system operating now and fully heating and cooling a residence in Atascadero, California. The system was earlier described in the technical literature (Mech. Eng., Jan. 1970) and ignored in a manner it no longer is. The cooling is based upon nocturnal radiation plus indirect evaporation and heat transfer in Arizona and upon radiation and the thermal flywheel of heat storage in Atascadero. The system does not attempt to overpower the climate as do conventional heating and cooling systems but rather to work with it - to select from the climate the potentials for operating on the comfortable side of a mean daily temperature which is outside the comfort zone. While not always able to maintain a year-round narrow comfort range, it can stay within the President's prescribed range of 68^0 for heating and 70 or 80^0 for cooling a residence in many parts of the country and in a portion of the house most of the year in most of the country. Like other solar heating and cooling systems, it may need supplementary conventional devices in some areas part of the year but unlike these other systems it provides both heating and cooling at low initial cost and is operative throughout blackouts.

Attendees of this workshop have received copies of an article published in ASHRAE J., December 1973, in which John Yellott, Chairman of the ASHRAE Committee on Solar Energy Utilization, states; "The simplest system which can accomplish both heating and cooling with the same equipment was used in the Hay Skytherm house... The Skytherm system is capable of many modifications and the cooling effect of water which is subjected to both nocturnal radiation and evaporation must not be underestimated." In testimony before a Senate Subcommittee, Yellott said, "The evaporation in 1 hour of 1-1/2 gallons of water would be the equivalent of 1 ton of refrigeration; fuel and the cost, of course, would be only a fraction of the cost of electrical refrigeration."

The construction and results of a Skytherm test room built in Phoenix was described in the ASHRAE 1973 article in the following terms:

"This system is primarily suitable for use in the southwest where snow is not encountered and dewpoint temperatures are characteristically low. It uses a water-covered roof to collect solar radiation during the winter and to reject the daytime accumulation of summer heat by radiation and evaporation to the sky. Movable horizontal panels of weatherable urethane insulation are used to retain the heat collected on winter days and to prevent the sunshine of summer days from being absorbed by the water. During many weeks in the spring and fall no movement of the insulation is needed because of the natural "thermal flywheel" effect of the heat storage in the building and its water roof."

"During the summer of 1968, the combination of nocturnal radiation and evaporation was sufficiently effective to keep a prototype Skytherm building in Phoenix within the comfort zone during 90% of the summer hours, and below 85 F at all times despite the fact that the afternoon temperatures consistently exceeded 110 F. No electric power was needed with this system, although the expenditure of 0.10 hp for the operation of a small fan-coil unit improved the sensation of comfort by creating a moderate amount of air movement. The first full-scale Skytherm residence is now in operation at Atascadero, CA, as a joint project of the inventor, Harold Hay, Calif. Poly. State Univ. at San Luis Obispo, and HUD."

Extension of the climatic range of the roofpond system from the hot and dry and hot and humid climate of Phoenix to the slightly more northerly, more cloudy, and colder climate of the California valleys, resulted in confirmation of the system's value and in several modifications useful for other climates. The Atascadero house has only 100% of the floor area as roofponds compared with 120% obtained by using overhangs on the Phoenix building; thus overhangs are reserved for water heaters and solar stills. The improved heating efficiency, the automation system, and other major design advancements, resulted from the evaluation study by a team of eight professors at California Polytechnic State University under the leadership of Prof. Kenneth Haggard of the School of Architecture.

The waterpond system presently in use on the Atascadero house consists of a black waterproof plastic liner over a waterproofed steel deck. Above the liner, between the beams and trackways, are 8-foot-wide ponds averaging 10 inches deep in clear PVC bags similar to waterbeds the full length of the roof. The plastic film above the water and that of a gas cell (filled with nitrogen) over the water are of UV inhibited PVC. Use of the gas cell increased winter collection efficiency to 43% at midday. The efficiency can be further increased by known methods and should permit the use of roofpounds in even more northerly mild climates.

Some conclusions from this evaluation conducted for the U.S. Dept. of Housing and Urban Development, indicate the scope and success of the system.

Architecture

"From the viewpoint of use of interior space, roof ponds have distinct advantages over prior methods of storing collected solar energy." "The horizontal roof pond accommodates space planning and design with more flexibility than was thought at first." "No difficulties were encountered in getting building permits with inspections nor from mortgage or insurance companies."

Construction

"The moderate roof load of the water ponds requires a small increasing in footing widths but the loading provides no major problems in an earthquake area nor on expansive soil... The concentrated loading of the water tanks or rock bins used internally in some prior solar houses could present greater problems."

Automation

"This sol-air temperature controls the movement of the insulation panels..." "The complete mechanical system at this time is operating satisfactorily."

Economics

"Preliminary analysis shows the cost of the system to be slightly greater than normal roofs in the area with the strong possibility of the costs becomming very near the norm with some post-prototype modification." "It has promise for being competitive with conventional heating and cooling in the Southwest."

"At this stage of the investigation...based on imputed figures rather than actual experimental results, we can conclude that this type of solar housing will probably save about 5% in the annual housing expenses for the consumer and about 1% of the energy consumotion for the country as a whole."

Thermal Results

"At no time during this early February period (or any time during the three months plotted) did the occupants use any auxiliary heat, although they were free to do so." (Note: in this 17-day period, 11 days had temperatures at or below freezing: day and night average was 45^{0} - the winter temperature for which the house was designed.)

Occupancy Reaction

"The family considered hot weather thermal control far superior to that of conventional air conditioning. Quietness, eveness of temperature, lack of air drafts, and comfort when changing from active to passive patterns of daily life were noted along with the belief that it is easier to go to sleep in this house."

"The family's response continues to be very favorable during cold weather occupancy as was the case in the hot weather cycle. Their comparison with their own conventionally heated home (gas furnace) was that the test house was 'distinctly superior.'...the family expressed full satisfaction with the test house capabilities of meeting their comfort range requirement."

"...the 'feeling of heat' was different in the test house in that the humidity level was much more comfortable to them in comparison with their conventionally heated home which always 'felt' dryer." "The combination of these factors made the test house 'seem more natural' to them." "Overall, they feel that all qualities of the test house are distinctly on the positive side with respect to health."

It is important in a scientific evaluation to have an objective report on the subjective reaction of non-technical persons living in a test house. It must be recalled that the "comfort zone" and the "effective temperatures" are measured ranges of such human reactions. The hard data on thermal results will be analyzed, to the extent the very limited funds of this project permit, to determine the conformity of ASHRAE comfort standards and the reactions of the occupants of the house.

Expanding upon the economics of the roofpond collector dissipator-storage (CDS) system, the professors find that the first cost is $1.10 per sq. ft. above that for a normal ceiling, roof, heater and air conditioner and is apt to be lower in mass production. The maintenance, they state, should be slightly lower on a 15-year basis than for conventional roof, heating and air conditioning. Savings of $250-$300/year in fuel bills, expected by the evaluators, can be projected to the $240-500 range (or higher) in 1985. On a btu basis, the professors calculated that the house saves 42 barrels of oil per year which, at current prices of $15 barrel in some parts of the country, represents much higher economic potentials.

Prototype problems encountered during the evaluation included leakage resulting from failure to peripherally seal the water ponds where they contacted the metal roof. By capillarity, rain moved to a poorly sealed bolt hole. Also, the hollow metal beams acted as condensors to concentrate water from under the pond liners and may have condensed water from air passing through the beam. Some automation problems were likewise encountered which were of prototype nature and have also been corrected. The horizontal roofpond CDS system is now believed to be ready for production design and use in the Southwest and parts of the Southeast.

Attention can now be given to development of a snow-dumping, horizontal CDS system and other designs for inclined roofs and south walls. The use of movable insulation with one form of water storage in the south wall was proved effective by Steve Baer in Albuquerque, New Mexico. Other designs, some more complex, include a thermo-siphon action to circulate water in the south wall and to move it through plenums to remote rooms without pumps. The applicability of movable insulation as a thermal valve is as widespread as the potential use of solar energy for space heating. Movable insulation permits high heat capacity building materials to serve CDS functions.

Low temperature CDS has advantages of less reradiation from the collector. It is seldom desirable to collect at more than 80°F in roofponds serving as direct radiators to underlying rooms. If the midwinter potential for solar heating would raise a given water depth above

$80^{o}F$, the depth is increased; this not only provides more heat for sunless days but reduces the interior amplitude of the temperature range and it improves acoustical resistance to external noises.

Horizontal collectors, while less efficient than optimally inclined solar collectors at latitudes more polar than the Tropics of Cancer and Capricorn, collect more diffuse radiation than do the inclined type and are less costly. Horizontal dissipators are more efficient at all latitudes than are inclined ones. The collector inclined optimally for winter heating will be less efficient for absorption cooling in the summer. Glass covers are more efficient than plastic ones for collectors but less efficient as dissipators. The advantages of the plastic, horizontal CDS systems are, therefore dominant in much of the tropics and much of the American Southwest and Southeast. As with other solar systems, the use of supplementary conventional heating and cooling devices may be required when the insolation and other climatic factors are not adequate for comfortable thermal conditioning of space.

Architecture must be the prime solution for our energy crisis and the basis of use of natural heating and cooling. Less glass (on a doubled or tripled amount) becomes a necessity as does the use of heat storage in partition walls, floors and ceilings. With these, comfort can be maintained during peakload blackouts and power can be used to store heat or "coolth" during offpeak hours with loss of comfort. Horizontal roofpond CDS systems can be used in severe climates for one-story buildings or the top floor of multi-story buildings. In milder climates, surplus heat or "coolth" may be transferred from the roof to one or more lower floors by means of fantails.

For Atascadero, the concept of an architectural student, Russell W. Wong, includes roof ponds for 2nd floor heating and south wall fenestration and collectors for the ground floor. Because radiation only is expected to be adequate for rooms underlying the roofponds, the addition of indirect evaporative cooling would supply the coolth for ground floor rooms. It will be difficult to remain abreast of the many creative efforts of architects to design for minimum use of conventional heating and cooling devices.

We have gone the route of the overcomplicated and have created both energy shortages and pollution. We face the problems of insufficient money to generate and deliver the power demand and of adding such cost to heating and cooling that lower income families may be deprived of these aspects of the American Dream. In 1796, Edmund Burke said, "Economy is a distributive virtue and consists not in saving but in selection." It is my opinion that failure to select has brought us to the imperative decision that we must select the simple and proved principles of nature and live closely with the natural diurnal thermal balance - that we have no other option.

<u>A Solar House Economic in 1973</u>

The <u>only</u> solar house completed for full evaluation by the U.S. Dept. of Housing and Urban Development to help met the fossil fuel, power shortage, and pollution crises is shown below in photos. A team at Cal. Polytechnic State U. (San Luis Obispo), headed by Prof. Kenneth Haggard, is evaluating the architecture, construction and maintenance, thermal and acoustical performance, economics, and occupant reaction. During this one year of unique and comprehensive evaluation, the house is not open to the public.

At 7985 Santa Rosa Road, Atascadero, Cal., the 3-bedroom house is now occupied by a family of five. Designed by Environmental Planning Consultants, the house has complete <u>natural</u> heating-and-cooling which does not distort esthetics, does not occupy floor space, nor requires circulation units.

Integrated concrete block and wood construction shows versatility of materials and architectural effects. Results are best with new concrete or metal construction, which may be conventional in appearance. SKY THERM is not limited to the one-story, flat-roof style shown; designs are under development for southwall heating in northern and snow regions.

SKY THERM provides new, more comfortable standards by mildly heating and cooling through an acoustical metal ceiling - no hot or cold spots, no air drafts or noise. Regular building materials are the heating and cooling system; hence low initial cost compared with conventional design.

Comfortable throughout several sunless days, this solar house has no electric pumps or fans which would be inoperative during power blackouts. Earthquake design, codes, and insurance presented no special problems. Until generally accepted, any solar design may require higher mortgage down payment-minimal with SKY THERM because adaptability permits adding a second story or the addition of supplementary heating and cooling.

Over the metal ceiling, a double, impervious plastic liner is under these waterbeds; above are panels of movable insulation. In winter, the uncovered waterbeds are solar heated; automatic closing of the panels prevents nighttime heat loss. In summer, heat absorbed from the room is stored in the water until the panels, which then prevent daytime solar heating, move aside to allow nightsky cooling. Phoenix, Arizona, tests established that SKY THERM Natural Air Conditioning required no conventional heating or cooling when air temperatures ranged from subfreezing to 115^{0}. This result is unequaled by any other system for solar energy use.

A 1/2 hp motor running only two minutes morning and night (or manual operation) moves the insulation panels (thermal valves) on trackways from over waterbeds to a carport or patio area for 3-deep stacking. In some climates, a little more electricity may be needed.

Only SKY THERM has developed a modular roof system of interchangeable, patented units that provides thermal comfort, solar heated and nightsky cooled water supply, and distilled water from solar stills.

Fig. 1

Fig. 2

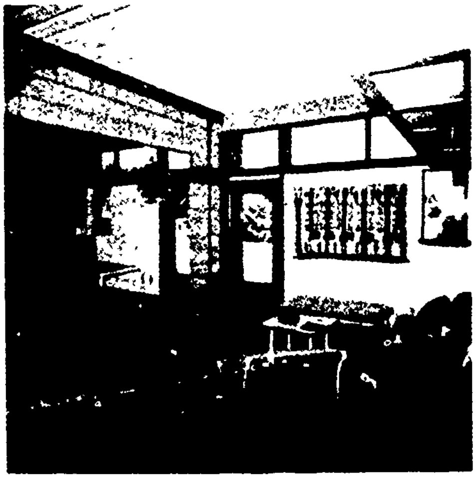


Fig. 3

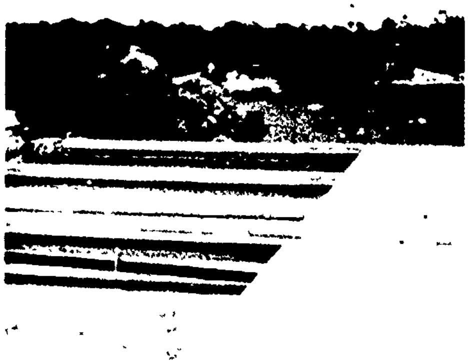


Fig. 4

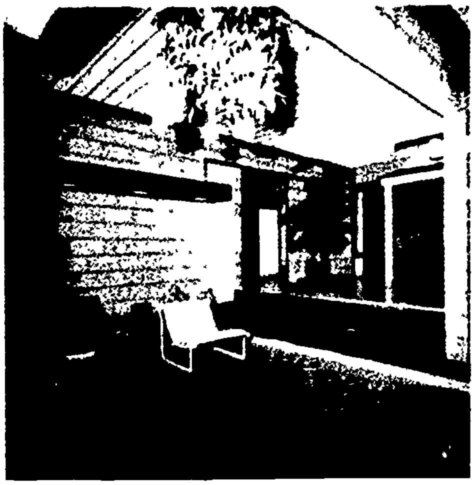


Fig. 5

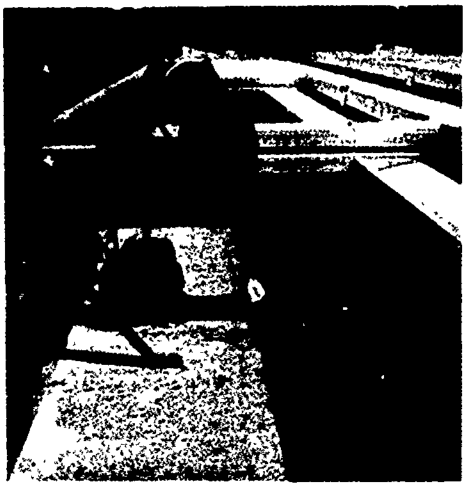


Fig. 6

A HEAT ENGINE USING CRYSTAL TRANSFORMATIONS

Ridgway Banks

Lawrence Berkeley Laboratory

The Banks Engine

I want to introduce to you a novel not to say perhaps wild, energy conversion approach that we've been working at at the Lawrence Berkeley Lab since last August. This is a heat engine that works at low temperatures across a small ΔT. It uses not a fluid, but a crystaline solid as its working element. The solid we use is a homogenious nickel titanium alloy called "Nitinol:" Ni for nickel, Ti for titanium, and Nol, for the Naval Ordinance Lab in Silver Spring Maryland where it was discovered in 1963 by W. Buehler.

This is a most unusual alloy and I will just stick to the parts that are interesting as far as we are concerned. It undergoes a phase transformation at a fairly low threshold temperature. It has two crystaline forms, and at the threshold it will switch between these two phases. What this means practically-in terms of using this alloy as a conversion element is that you can imprint a shape memory on the metal by heat treating it at fairly high temperatures and then when it comes back down to normal ambient temperatures, you can recall that shape memory in the wire by small temperature changes.

I think there are a couple of aspects to this wire which are of interest in the engine application. There are questions that come immediately to mind that I will have to address sooner or later, so I might as well do it now.

The first question concerns fatigue, since here is a metal obviously undergoing a radical change of shape. What does this do to the inter-crystaline structures? The situation in most metals and most substances, is that if you exert a force you get a gross deformation along fairly long fiber or unit lines. In other words, most metals tend to propagate an elastic stress like a kind of metallic crawl, and if you cycle them back and forth after a while, they break. What happens in the Nitinol in the transformation (which is a martensitic transformation) is similar to a phenomenon that occurs in steel when it comes down from high austenitic temperatures. What we think is the mechanism for this transformation are very small localized changes. There are little shears that take place along the crystal lattice boundaries. This could be illustrated with a pack of cards, you can slip them sideways, there can be a gross overall deformation but in terms of the lattices here represented by the playing card, the movement can be very small. It would be an accumulation of many small localized movements. The martensitic transformation is a diffusionless shear in which the nickel and titanium molecules move to create a new crystal structure, but each atom of nickel or titanium moves less than one total interatomic distance. They don't get in each others way, and you do not have the kind of elastic deformation that produces work hardening and fatigue. We have cycled the wires in this engine for more than 10 to the 7th cycles and they're just as good as they ever were.

One other question that will come up, I think probably, is that of the effects of corrosion on this material. One of the aspects we like most of this approach is that you can use the working element in direct contact with the heat medium. Whether it be ocean water, salt water, whether it's geothermal brine, whether it's industrial effluent, you can stick this material right in your heat source without any intermediate heat exchangers because this nickel or titanium intermetallic compound is notoriously corrosion resistent.

One other question would have to do with what kind of temperatures or ΔT's that you can work at. We don't have a firm answer on this. We think we can work very conveniently with 40 degrees C and probably with pretty good efficiencies at half that. Normally we run the engine at about 24 degrees C but then the laboratory caught wind of the energy crisis and they did their bit by turning down the hot water boilers in the building where the engine usually runs, and that slowed it down a bit. The other significant thing to bring up here is that the threshold temperature in which this transformation takes place can be manipulated by changing the composition, by changing the proportions of the nickel and titanium in the wire. That can be changed over a 300 degrees C range from -150 to +150 degrees C. There are tricks at the very low temperatures. But what I'm saying is that a wide range of applications open up when you stop thinking of absolute temperatures and start thinking more in terms of ΔT which can exist in many places on the thermometer.

The calorimetry of this material is extremely difficult to do, and the literature is very inconclusive on it. There are many interdependent variables here. The thermal characteristics of the wire and of course the mechanical ones vary very much as they go across the transition temperature. In going across the martensitic transformation the specific heat changes too. So it's hard to say exactly what the efficiencies are, or what they will be when we learn more about this material and how to use it.

(A film was made of the operation of the engine of the Banks No. 1 Nitinol engine shown in Figure 1, and shown to the audience. Operation included both bench tests and operation on solar energy with a stationary flat plate collector. Electricity was produced.) The following is the narration during the film:

Here is the engine on the first day that it ran. It ran very well right off and that never happened to me before. Not only that, but instead of stopping and fouling up, it got better after it ran for a few days. We're trying to show here how the wires open when they are in the hot side. There is a good deal of force in each wire. When they go on the cold side they relax, and are reshaped into loops. Now in point of fact, after we ran the engine for a while, we found that they were closing spontaneously, at least 50 of the distance. That's why the engine ran better because we weren't losing the work in closing them. This wire has a tendency to program itself, to conform or to optimize itself to the cycling situation. Now we didn't know that until we did it, because no one ever continuously cycled the wire in engines before.

You can change the speed of the engine by changing the pitch on the crank shaft. In other words, you phase it. When it goes fast it takes a while for the wires to drop in, so you move that crank shaft off almost to 9:00 o'clock. In Figure 2 we're generating electricity. There is no threat to your eyesight, but we did it with hot water and 20 six-inch loops of this material. A total cost of \$3.50 for the working material.

Here we're lifting a weight-I want you to see that it says 10 kilograms on it. It's a lie. It's a counterweight actually. It weighs about two pounds.

This is a lot of fun: we're on the roof of the building now (Figure 3) and this is a stationary flat plate collector. We're going to generate electricity, but you know about that. This is just a vinyl black bag with a booster bank of reflectors behind it. The tubes are on the top of the collector. Okay, so now we've made the cycle from solar heat to electricity in a ridiculously small way, but we did it through this solid state energy conversion system. These tubes are simply commercial glass tubes eight feet long by a little bit more than two inches wide, and intended to be made into fluorescent light bulbs. They cost 21c a piece. If you buy more than 1,000 they go down to 11¢ - (That is the kind of weather we had that day when we did that, that was in November. I was too excited to put on my parka, but it wasn't a very hot day). The thing about the glass. The cost of glass in this form - I figured it out, - is less than 16c a square foot. I think you might consider this, because it's also strong and it's modular.

Later a live demonstration of the engine was held for the workshop in a hotel bathtub.

A HEAT ENGINE USING CRYSTAL TRANSFORMATIONS

Paul Hernandez

Lawrence Berkeley Laboratory

Phase Transformation of Nitinol

Nitinol is an equiatomic intermetallic compound. 55-Nitinol nominally has 55% nickel and 45% Titanium by weight. Mechanical memory, the property that causes the Banks Nitinol engine to function, is set at a temperature well above the transformation temperature range, TTR (Buehler and Cross, 1968). The Nitinol is held in the desired shape to be remembered, in our case straight, and then annealed at a temperature of 750 to 1200°F. Lowering the annealing temperature will give a higher uniaxial expansion when transforming from NiTiIII to NiTiII (Figure 4). NiTi melts around 2390°F. The two phases of interest are the NiTi III, which has a rhombohedral crystal structure, and NiTiII that has a cesium chloride structure. The memory recovery is associated with a martensitic phase transformation from the cubic structure high-temperature phase to a lower symmetry (probably rhombohedral) low-temperature phase. The transformation on cooling starts at the M_s (the maximum temperature for martensitic transformation by deformation) temperature on cooling.

Nitinol has two types of uniaxial expansion and contraction.

1. The ordinary mean coefficient of thermal expansion is 5.7 x 10^{-6} per °F.
2. The large transitional expansion from NiTiIII to NiTiII is irreversible and can be as high as 0.8%. A lower anneal temperature gives a greater expansion, but for good memory characteristics the annealing temperature is around 932°F which gives about a 0.3% expansion. Temperature transition ranges are from 165°C (330°F) to nearly liquid nitrogen temperature, about 77°K (196°C). The transition temperatures can be lowered by increasing the amount of nickel or by substituting cobalt for nickel.

The phenomenon of real interest in the Banks Nitinol engine is the idea of mechanical memory and optimizing ways to get work out. To describe the phenomenon, start with Nitinol cooled below the M'_f point (temperature where transformation to the low temperature phase is complete). Deform the metal plastically about 6%. This causes further transformation to the low temperature phase. The critical stress for this type of deformation is very small (10^3 to 10^4 psi).

The Nitinol is now heated through the A_s point (the austenitic start temperature, and the transformation from NiTiIII to NiTiII begins. The transformation continues through the M_d. Between the A_s and the M_d points the Nitinol returns to its "remembered" or predeformed shape. Strong energetic and directional electrons in the covalent bonds are believed to pull the displaced atoms back to predeformed positions.

The Nitinol can now be cooled through the M_d, M_s, and M'_f points where the memory or energy cycle can be repeated. In an engine the plastic deformation is put into the wire when it is in the low temperature phase when it is very soft. almost like a soft copper wire. It only takes about 1/10 of the energy to deform it cold as it yields when it is hot. When it transforms from the rhombohedral phase into the cesium chloride type crystal, it becomes as strong as stainless steel wire. It reaches a yield strength of above 100,000 PSI.

So now the trick is to recover the initial strain, which was plastically deformed in the soft phase. When the nitinol is heated through its transformation temperature it will actually shrink back to its original dimension. This piece of wire which is four inches long, if you just pull it, 2/10 of an inch in the soft state, put it into hot water, it shrinks right back to its original dimension. It is this work of recovery that you try to get out of the wire.

Potential Work Output and Cost of 55-Nitinol

If we look at the maximum mechanical work curve for 55-Nitinol we can get an idea of the potential work available. Figure 5 is from a study by Cross et al (1969). Right now we're way down on the learning curve, at a strain of about 1%. The target we'd like to reach is about 5% initial strain and the work cycle repeated indefinitely. This value is far more than any type of normal elongation that you run into.

For this tentative case the mechanical work released per cycle, from Figure 5, would be 1250 in-lbs/in^3. Before 5% can be considered a design value, however, a fatigue test will be required at various strains to determine the highest usable cycle strain for an engine designed to run indefinitely. The original Banks engine has run about 15 million cycles at a cycle plastic strain of less than 1%.

The energy per pound for 5% strain would be 605 joules/lb (1250 in-lbs/in^2 x .1132 joules/in-lb x 1/.234 in^3/lb). If we could run that engine at a speed of 50 rpm (2/3 rps), which is about what we have been running the present engine load, that would yield about 403 watts/lb. At $60 a pound that would give a cost per kilowatt of about $150. That's at December 1973 research quantity prices. Now we expect that in time, and in large quantities, that the cost would come down at least by a factor of two. So as a target, say we're looking at $75 per kilowatt, for just the nitinol content of the engine. These cost indicators are of interest when it is considered that today's nuclear power plants cost about $340 per KW and those now on the drawing boards will cost close to $1000 per KW in the 1980's when they are completed.

At this point, with the possibility of obtaining 600 joules/lb and a potential cost of $75/KW, Nitinol looks competitive economically If engine speeds can be increased, the power rating will increase proportionally and the cost per KW will decrease inversely proportionally.

To date we have attaind the following mechanical work values.

	J/lb	W/lb	rpm	$/KW
Banks #1 engine	10	9.1	55	3270
0.064-inch-diameter wire test	30	30	40	960
0.020-inch sheet test	80	80	40	370
Long-range design objective	600	400	40	75

The work required to reset the 0.064-inch-diam wire in the cold temperature bath is 7.2 in-lbs/in^3 (3.5 j/lb); from Figure 5 it is seen that this value is negligible. The Banks engine works the Nitinol in bending and the energy released is only 1/4 that of a rod in tension. The stress and strain are maximum at the outer edges of the wire and zero at the center. The long-range objective case assumes that the Nitinol is strained uniformly such as in tension as shown in Figure 2.

Now the size: if we work in 20 mil sheet, we could have a 1KW engine with say 50 blades about an inch wide and about 10 1/2 inches long, so we'd have a unit that's only about

24 inches in diameter and about 6 inches high for a kilowatt. That still allows what we think is enough for heat transfer area. Nitinol working at 1250 in-lbs/in^3, and using 0.020-inch-thick Nitinol sheet, whose properties are presently only partially known to us, would yield the following:

$$1/.403 = 2.48 \text{ lbs/KW}$$
$$2.48 \text{ lbs} \times 1/.234 = 10.6 \text{ in}^3$$
$$\text{area } 10.6/0.020 = 530 \text{ in}^2$$

or 50 blades each 1-inch wide and 10.6-inches long and 0.020-inches thick. The heat transfer surface would be 1060 in^2 or about 9 W/in^2 (491.8 btu/hr ft^2), a very conservative value. The value of 1250 in-lbs/in^3 has only been attained in 0.020-inch diameter wire working in tension.

Engine Speed and Heat Transfer

Since the amount of power derived from an engine is porportioned to its speed (rpm), it is important to increase the speed to an optimum value. To do this requires transmitting the heat in and out of the Nitinol by conduction and through the film to the water rapidly. Rapid heat transfer will bring the Nitinol to a more uniform temperature so that it will develop the highest average value of work. Another consideration is the temperature difference required to drive the Nitinol phase transformation rapidly. Operating with hotter and colder bath temperatures will speed the reaction.

Now, Nitinol has heat transfer characteristics much like austenitic stainless steel, it is really hard to get the heat in and out, so that implies using small diameters, or to use it in sheet form.

The thermal conducting properties of normal Nitinol and Nitinol in the transforming phase bracket those of austenitic stainless steel (300-series) as shown on Figure 6. The first Banks engine uses 0.048-inch-diameter (1.22 mm) Nitinol wire for its driving elements and has an engine speed of 55 rpm at peak load and from 65 to 70 rpm without load. At present it is known (see Cross et al, 1969) that 0.020-inch (0.5 mm) diameter wire in tension releases the highest mechanical work per unit volume (2900 in-lb/in^3 at an initial strain of 7%). Also the conductive heat transfer rate for 0.020-inch-diameter wire is faster than for 0.048-inch wire. However, many small wires would complicate and increase the cost of an engine. These considerations suggest that the sheet form of Nitinol is a good candidate, but its mechanical work property will have to be determined.

Work to Do

Now, when we talk about 15 million cycles, that is for our present engine which is working at about 20 (in-lb)per cubic inch. So we like to improve the engine so that it is operating at about 1250 (in-lb)/in^3. The present engine uses the wire in bending where the outer fibers are at the maximum stress and the center fibers are at zero stress. When you integrate the stress together with the face that is's a round wire, the peak energy will only be 1/2 of what you can get if you pull the wire in tension. But that's okay, that would give us enough to prove the concept. When we work down at 1/2 to 1% longation where we are getting that 15 million cycles, we have to do three things. We have to increase the initial strain and see if we still get long life. Secondly, we have to do a heat balance. We can handle the specific heat in and out of the wire and I don't think that is going to be too difficult. However, there is also a heat of transition that is associated with the phase transformation and that is one we have to go into and see exactly what that is going to do to the thermal efficiency. At present with the engine working down in the 1% elongation range we are not converting too much of the material.

Besides the heat balance and the fatigue, the third thing we'd like to do is study the fracture mode of a fatigue failure. We have an inorganic material laboratory at Berkeley very interested in this failure mode. They want to cut discs out of 48 mil wire and then etch them down to a quarter of a micron. They will then look at them in a transmission electron microscope and watch the martensitic transformation take place to determine if it is a type of transition that is reversible. So with those three things are our main efforts of work. What we really would like is to have the opportunity to keep on finding out the answers and to develop this into a better engine.

Conclusion

At this point the development of the Banks Nitinol engine has the potential to be economically feasible for low-temperature-difference (about 45^{o}C) applications. An engine working a low-temperature-difference is an expecially good choice where the higher temperature already exists, otherwise engines operating on low Carnot efficiencies require heating disproportionate amounts of fluid. Examples are:

- A solar-powered engine for building air conditioning applications used to drive a vapor compressor.
- A solar-powered engine for building heating applications to drive a blower to distribute the heat.
- A solar-powered engine to drive an agricultural water pump. The well water would be the cold sink.
- A Nitinol engine driven by waste heat from an electrical power generation plant sited to use ocean cooling water.

We are currently doing some testing and optimizing engine element design. Our objective is to construct a reliable and economical Niti ' engine. Our motivation is the use of Nitinol in a low-temperature difference engine at a potential cost of around $75 per KW. We see many reasons for going ahead.

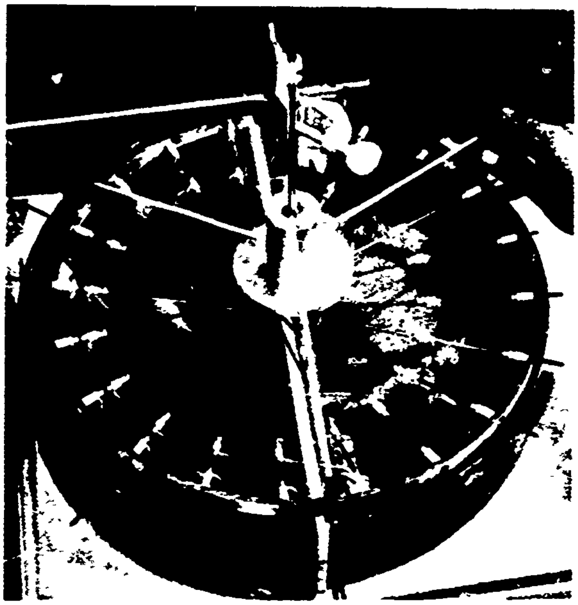


Fig. 1. The First Banks Nitinol Engine

Fig. 2. Glow from a small light bulb signals the successful generation of electricity by the Banks engine. Sclar Collector stop LBL physics building supplies the hot water to drive the engine

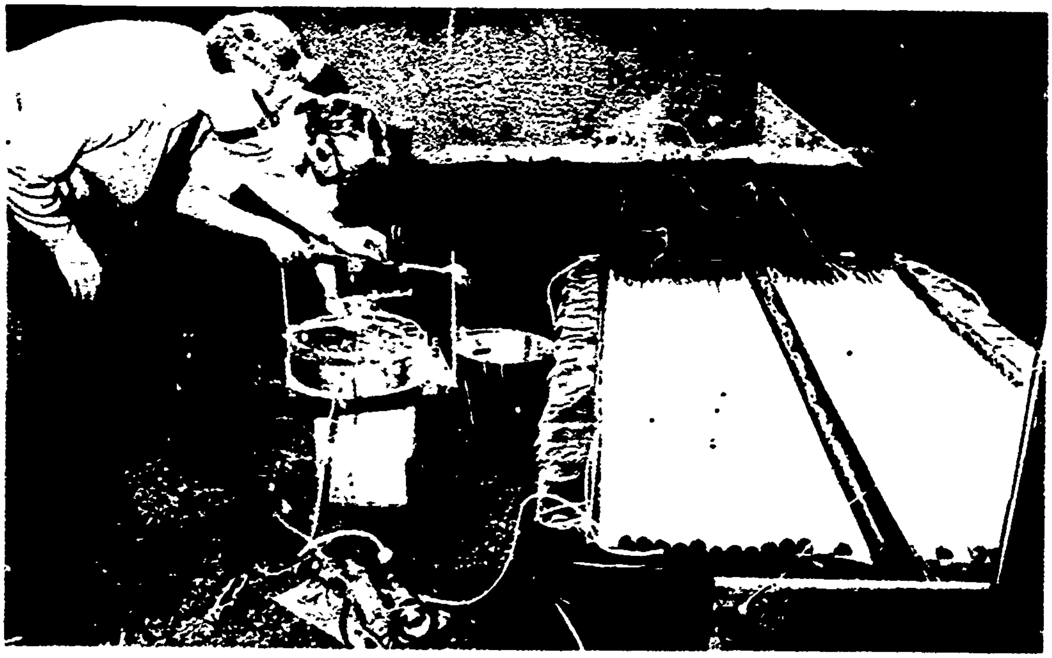


Fig. 3. "Solar Heat to Electricity in a Ridiculously Small Way"

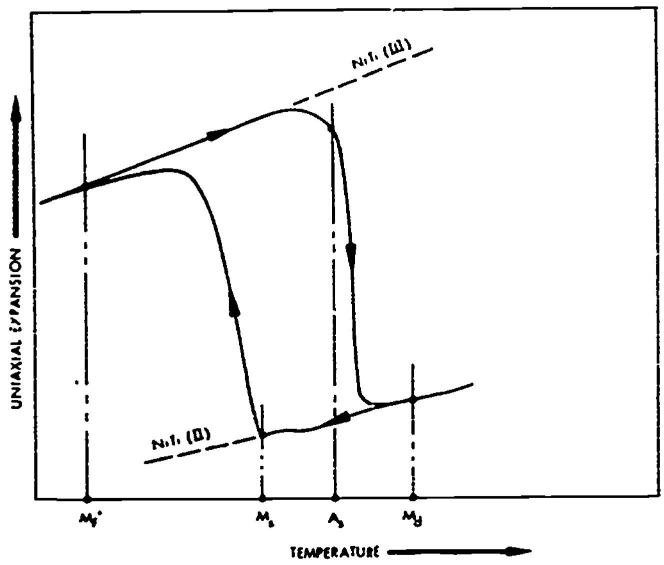


Fig. 4. Typical uniaxial dimensional behavior. The near horizontal paths along the dashed lines NiTe(III) and NiTe(II) represent the normal thermal expansion coefficient which is about 5.7 x 10^{-6} per ^{o}F. The near vertical paths are expansions caused by the transition from NiTe III to NiTe II and return any range from 0.3 to 0.8%

(Cross et al, 1969).

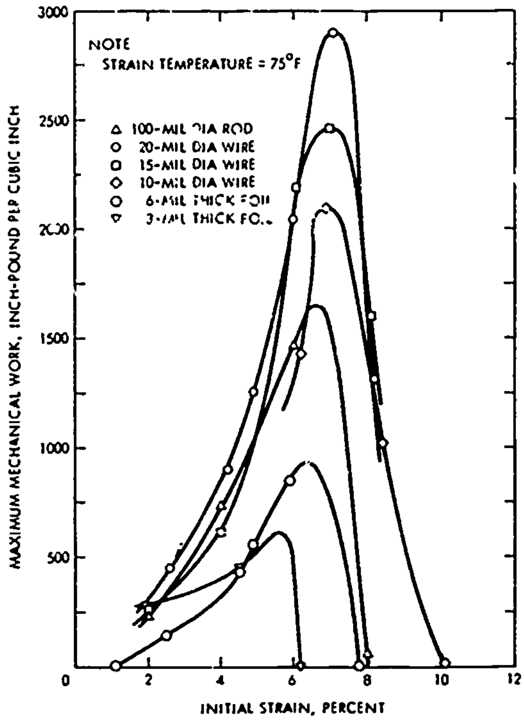


Fig. 5. Maximum mechanical work available from Nitinol shown as a function of the initial strain and material shape and size (Cross et al, 1969).

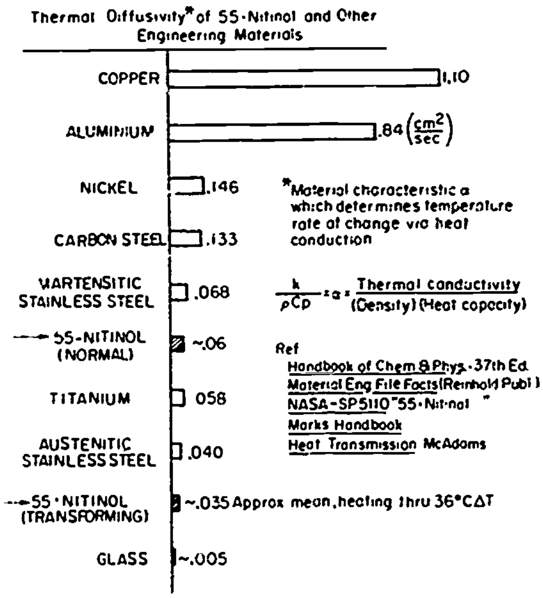


Fig. 6. Thermal diffusivity of 55-Nitinol and other engineering materials

[illegible]

Commentator: William Beckman

University of Wisconsin

Questions and Answers:

Beckman: First question is to Peter Lunde. How sensitive is the system performance to the humidification water addition temperature?

Lunde: I don't think it would be very sensitive. All the preliminary numbers I ran presume that the water is at the adiabatic saturation temperature. You would lose from your air conditioning performance that amount of heat necessary to cool the water to the adiabatic saturation temperature if I remember my thermodynamics correctly.

Beckman: Is the author familiar with the large Australian work in silica gels, and if yes, would he please comment on their findings on solar energy-silica gel combination usage.

Lunde: I guess I was just talking outside with gentlemen who also proposed that question. No, I'm not familiar with it. We've looked up silica gel in the literature and found a very little even on the equilibrium model or equilibrium capacity and nothing on the dynamics. I'm not aware of the Australian work but I will look it up. It apparently appeared in the Solar Energy Journal. They decided that silica gel could not be regenerated in the 150 to 200 degree range, but I can report that I've done this in a one pound bed in work that I did not discuss in the report tonight. So I guess there is a conflict there.

Beckman: That's all the questions. I might make a comment that I'm somewhat familiar with the Australian work. It was actually done by Bob Dunkel and Don Close and I think if you were to write the CSIRO Mechanical Engineering Division they would have all of the necessary information. We have one written question, actually it was asked to any one of the number of people but we'll ask Bill Rush. Can solar heat at 200 degrees F. be used to regenerate a desiccant with no auxiliary heat source? Is that a tradeoff between regeneration temperature and residence time?

Rush: There are two things you have to remember when you are going to regenerate. The number of BTU's that you put into the wheel must be sufficient to evaporate the number of pounds of water that have been adsorbed on the wheel. So theoretically, 200 degrees could do the job for some relatively low amount of water matching the quantity of energy that you're going to put in the wheel to regenerate. However, in the next instant when the wheel becomes a desiccant again on the desiccant side there has to be a driving force between the partial pressure of the water vapor in the air and the equilibrium temperature concentration on the surface of the desiccant when it moves into that zone. So, there is some point at which 200 degrees F is sufficiently high, but I don't know exactly to what ambient that would correspond at which you would need absolutely no auxiliary heat. One of the nice features this system is that if your collector is at 200 degrees for example, you would only need about 50 of the gas energy you need at design. As the ambient conditions become milder, then 200 degrees may be able to supply 90, 95 of the energy required. By being able to couple with a thermal booster in this system, stored fluid is supplied at whatever temperature above 175 degrees F, say 190 degrees F, or 200 degrees F, you can use every bit of that energy that is possible to be transferred into the system at the low temperature level and then top it at that point. Unlike other types of systems, it is conceivable that the temperature you have to deliver will leave the system at a higher temperature than the collector is operating on that day. We'll never run into that problem with the MEC system because we can use the energy at the temperature that exists in storage and put it into the system at that temperature level.

Beckman: At one point it bothered me, I think it was during the heating cycle that you indicated energy from the collector at 230 degrees and you didn't need it so you used a very poor heat exchanger to reduce it to something lower. It just seemed, it sent shudders up and down my spine to see that kind of thing.

Rush: No, again we will use whatever temperature is stored, but remember the peaking problem. At 230 degrees and with the heat exchange area that we have in the unit we would deplete the stored energy too quickly. Also, if we had 230 degrees stored the air coming into the heat exchanger would leave at 220 degrees. It would then transfer the 220 degree air to the other side where it would come off at 210 degrees F - which is just too hot to put back into ones house. So what I would like to do, is prorate that usage of stored energy. Take the 230 degree air, use only part of the heat exchange surface, return the fluid to storage at 220 degrees, by taking the 10 degree drop, but only heat the incoming air from room temperature to 123 degrees. At that usage rate one can use whatever stored energy selected to be prorated over a 24 hour period for even a zero degree day. You use just the amount of natural gas required to deliver the 155 degree air for the amount of solar energy needed on a 24 hour basis. Thus, both are used equally over that whole period of time.

Beckman: One question for Sean Wellesley-Miller. Could you please describe the size of the projected unit, its output, efficiency and/or life as you are sort of designing towards?

Wellesley-Miller: If I knew the answer to all of those questions, you wouldn't need a grant to develop that system. The size the modules will be about four by eight feet. The efficiency will probably close to that for an absorption cycle. Design life is 20 to 30 years and we hope the payoff time is 10 to 15 years.

Beckman: We have a couple of questions for Benjamin Shelpuk of RCA. Could you give us some efficiencies, powers or significant performance characteristics of the VM machines that you actually showed in your presentation? I guess what is asked is why you did show some ready made pieces of equipment. Could you tell us how they actually did perform?

Shelpuk: Yes, the refrigerator I gave the performance on was a three watt refrigerator and the input as I indicated was one tenth pound of propane per hour at 20,000 BTU's per hour would make it 2,000 BTU's per hour. The output of that machine is 15 watts of mechanical work, three watts of refrigeration at 77 degrees Kelvin. The burner is roughly 40% efficient, so that input energy is 4/10's of 2,000 BTU's which would be 800 BTU's or roughly 220 watts.

Beckman: Plate type regenerators have been characterized by conduction along the gradient. How do you prevent or minimize this?

Shelpuk: To achieve optimum performance in a regenerator one needs to achieve the same temperature gradient in the regenerator that exists in the gas flowing through it. In a cryogenic regenerator, for instance, where you might be regenerating from 300 down to 77, you want that same profile to exist in a regenerator. That's why you break up the conduction paths and create insulated heat stations in that direction. Now, what we're proposing in the plate type regenerator is to go to a foil. When we get a ratio of heat transfer area to back conduction area, that gets sufficiently high, the regenerator acts like it's partitioned in the flow direction. It's strictly a matter of the ratio of heat transfer area to back conduction area. When you go to a very thin foil of low conductivity, three, four five mils, you tend to eliminate that problem.

Beckman: It seems like an obvious solution. I wonder why it was posed as a question in the first place. Is it a problem that has come up in the past? To make plates is an obvious way of eliminating conduction, and I wonder why the question was posed. Have people built these systems with thick wall plates and have had trouble?

Shelpuk: I don't know a lot about gas turbine regenerators, and the gentlemen who asked the question may be familiar with them, and maybe that's why he's asking the question. I would think that in a gas turbine where you have very high temperature that you've got a problem of erosion and chemical attack to the regenerator. We're talking about room temperature, and I think that the very thin foils will stand up in this kind of condition.

Beckman: Have you included: 1) self motivation power in your analysis and I really have to admit that I'm not sure what is meant by that.

Shelpuk: Well, I talked about self motivation power in the first photograph that I showed, and the answer to the question is, no I have not included self motivation power. That certainly is a thing that I think we would want to put into an ultimate device but I think we want to walk before we run.

Beckman: Have you included auxiliary power to any of your COP assessments?

Shelpuk: No. We have not included auxiliary power in the numbers shown in the analysis and there would be an additional 600 watts required to drive the auxiliaries to the system.

Beckman: How did you actually propose to get 300 degrees out of solar?

Shelpuk: Well, we analyzed the refrigerator under two conditions. We analyzed it at 350 degree temperatures and we analyzed it at 200 degree temperatures. We did that for good reason. The machine performs better at 350 degrees and there is some indication with high performance collectors, of types that various people have proposed that 350 degrees is something that one could speculate in the future. The refrigerator however will work at 200 degrees input heat and we clearly indicated what its performance will be under those conditions.

Beckman: So the 350 degrees is hoped for some future collector.

Shelpuk: The question was asked out in the hall to me was why did I cut it off at 350 degrees.

It was cut off because the question could have been asked how do you propose to get higher than 350 degrees?

Beckman: The final question is more in the line of a comment. The comment is I do not consider (it's not my comment I'm reading), 3500 PSI the hydrogen at eight hertz at all represents a practical machine.

Shelpuk: As I indicated in my discussion, that we have begun only recently to consider this technique as an air conditioning possibility and we feel as workers in the field that it is still difficult to describe the configuration which is best for air conditioning applications. When we applied our intuition to the design process, we didn't get a good machine performance. However, when we began to grind our computer, we found various combinations of regenerator configurations, pressure speed, geometry of the air conditioner that gave us a wide range of performance. My position is that one wouldn't begin an experimental program until he did a little bit more analytic searching and I think that the direction of the searching would be in the direction of reducing the pressure somewhat. On the other hand, 3500 PSI is not unusual. We have bottles of that type in our laboratory. I'm not proposing that it will be desirable to have a nitrogen or hydrogen bottle at that pressure in your home. But I think that it is not as undesirable as the proposer has indicated. We would look at that problem.

Beckman: We have a couple of questions for Paul Hernandez and Ridgway Banks that concern their wonderful machine. The questions are centered around with a bimetallic strip work in the same manner as the alloy is proposed.

Hernandez: Yes, it would, but I think I should let Ridgway Banks maybe answer this question, because that was the first step of the evolution.

Banks: I think it would, I want to do it. The efficiency of the bimetallic strip would be very low. It would be less than a tenth of a percent according to calculations that we made. This would really be an economic consideration. You'd need a terrific mass of bimetallic materials to get significant power out of a low temperature source. You have one little help there in that they're double acting. I'd like to see it done just for fun. I guess another serious constraint is that the bimetallic strips are typically nickel steel on an invar bond. They're not at all resistant to corrosion and so I think you would be constrained in your implementation. The efficiency figures that I've got for bimetallic strips-and this is off the page (I haven't really because when I found the nitinol, I dropped the bimetallics like a hot nickel, the other looked so good), would be in the order of .07%.

Beckman: Have you made any estimates of the ratio work output to heat required. I guess that is really a question about what is the conversion efficiency of the cycle?

Banks: We have only the crudest idea of efficiency at this time. We know that there is a heat of transformation of about 4150 joules/mole (39 J/gm) that will be transferred each time the Nitinol is heated or cooled. In addition, of course, there is the sensible (specific) heat on each side of the transition temperature that must be transferred. We have not done any calorimetry tests. Working with small temperature differences of 40 to 80 degrees K against an available ambient cold sink temperature of 300 degrees K will limit the Carnot thermal efficiency to 12 to 21%. Based on published data, a limiting thermal efficiency for the Nitinol can be envisioned as the ratio of the maximum work per unit weight per cycle over the heat of transition. The best reported value (Cross 1969) will yield a thermal efficiency of 7.9% (= 1400 J/lb work/17700 J/lb heat of transition). The target value that I discussed of 1250 in-lbs/in^3 at 5% elongation would give a thermal efficiency of 3.4% (600/17700). This thermal efficiency of 3.4 is (3.4/12 =) 28% of Carnot for a ΔT of 40 degrees K with a 300 degrees K cold sink. In addition, other losses such as friction, Cosine Law, effects of crank mechanism, and losses dragging the Nitinol through water must be added. It should be noted that efficiencies in this engine can not be improved indefinitely by increasing the temperature difference. If you assume a reasonable temperature difference of 40 degrees C, (because you see once you've established the hot phase and the cold phase, you don't increase the efficiency of the working material by increasing your temperature difference). So this is another peculiarity in terms of heat engines.

Beckman: Is the nitinol thermal elastic cycle reversible? In other words, can a temperature difference be produced by mechanical work on a shaft of the device, and if so, what are the prospects of a heat driven refrigeration device?

Banks: Yes, it is reversible. If you bend the wire-tanke a straight wire, hold it against your lip and bend it into a horseshoe shape vigorously-it gets quite hot. Then if you let it cool down in the same shape (constrained in a loop) to ambient temperatures and open that loop, it gets very cold. This is pretty unusual. Rubber will do this. For a practical heat pump I certainly wouldn't rule it out. The temperature difference has been noted as much as 15 degrees C between the exothermic and the endothermac reaction. It's certainly worth considering.

Beckman: The question is a comment. I saw a nitinol engine like this in an industrial lab three years ago. The problem was that the heat of warming and cooling was very high and the work output very low and for that reason it's assumed that they gave up the work.

Banks: I know of various projects that were initiated, using the ability of nitinol to work across a temperature gradient. The one that I'm most familiar with (and several people have spoken to me about this) is a spin off from the rubber band engine that was made by Paul Archibald from Lawrence Livermore Lab and reported a couple years ago in the Amateur Scientist section of Scientific American. I have spoken with Mr. Archibald, but I didn't know a thing about his work when I designed my first engine. Then someone charitably sent me a xerox of his thing, and of course his configuration is very much like mine. Then when I was trying to find a source of supply of the wire I got in contact with someone else at Livermore, and they told me to contact Archibald. A telephone call took place, and if you've ever seen two people playing it close to the vest. The verbal communication density of that telephone conversation was about the lowest ever. Later on he came and spent part of the day with us and we had a good time.

The trouble seems to have been in these early experiments, that they used the wire in tension, in linear tension and not in flexure. Now, initially, we thought that this was probably a fixture-related problem. You cannot exceed an eight percent fiber strain in this wire-you cannot simply bend it around a screw and clamp it down or it will break on you. As a matter of fact, I made history this evening with that little sample I was showing you, playing with it out in the hall I snapped one of the wires. If you respect the limits, you're okay. Of course we will have to push those limits until we have offended the wire to the point where it does fatigue. In the linear tension mode, I think there is another thing that happens here: we assume that the outer fibers of the wire and the outer crystals are more affected than the inner ones. I think Paul Hernandez brought this up. There is a serious question: What happens at the boundary there? At the interface between the two phases? It could be that you're setting up internal tensions that are going to require looking at, and this micro honing of the wires and looking at various cuts across the cross section with the transmission electron microscope should be very helpful there. Paul would like to know if the author of that question is here, what laboratory it was?

Beckman: One question to Harold Hay. I was wondering if he could come, and very briefly, tell us how well his house is actually performing today.

Hay: Today it's operating. Last week it wasn't. Water got under the water beds because the wood end closure wasn't sealed around the perimeter; rain moved back under the liner. The steel beam was wrong, another prototype thing; it turned out to be a condenser. Air entered between the waterbeds where waterbeds cross up and over the beams, water condensed inside, and drained down to the metal desk. The man who sold us the steel said don't put any holes in it, but the builder said "I can't weld it, it's much cheaper to drill holes in it." He drilled holes, water went in. These are prototype problems; we solved the rough ones, we stubbed our toes on the rather easy ones, and we are ready to go into prototype design.

The house went through the summer with a one degree 24 hour cycle; no thermostat is going to do that on a cooling cycle. This winter the automation equipment has not always operated and the panels of insulation hadn't been sealed. The wind blew between them, carrying a loss of three degrees a day under the worst possible conditions. This has been partially corrected so one may lose two degrees a day which means that with a ten degree reservoir there will be a five, six day heat carry through.

How is it performing today? When the roof ponds were put back into operation they went up ten degrees in temperature in one day. We're awaiting another cold spell to get solid weather data and will give you the answer then. Delays in developing a good automation system prevented us from getting complete summer data but that obtained was excellent.

There is no reason to be afraid of water on the roof. In 1966 in Germany, they started putting plastic film on roofs, not they're selling this in New Jersey. They've cleared the codes, the labor unions and everything else and what are they doing? Using a flat roof, covering it with a 32 mil layer of poly vinyl chloride and to keep the winds from blowing that away they ballast it with some river stones, or with water. So they already have the water pond up there. That's a going system that other people are introducing on the basis of wonderful experience. I think we'll also have the same results.

Beckman: We'll open it for general questions from the audience.

Richard Williams, Georgia Tech: I have a question for Bill Rush on his last slide. But he had the solar heat coming in at 230 degrees F. This is the gas assisted desiccant air conditioning system. The solar heat was coming in at 230 degrees but it was degraded, so the air was only heated to something like 130 and then you use gas. A gas flame to heat it on up to 200 and the question, is why use gas at all? If you have the solar heat available at 230, why not let it heat the air up to 200 degrees and not use the gas flame?

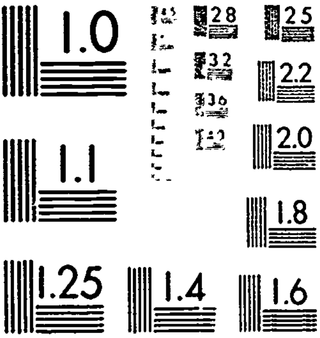
Rush: Okay, if you take the temperature drop that we show there, 230 down to 220, you will find that it will, over the 24 hour period exhaust one million BTU's. However, a 24 hour period at the design condition requires 1,300,000 BTU's. So I've got to put in 300,000 BTU's that I don't have stored. Now I have a choice. Put it in all at once in which case I deplete my storage at two in the morning or prorate it over a 24 hour day. We chose to do the latter.

Carl Lurch, University of Virginia: I wonder about the long term effects of such things as oil vapor that might be in the house. The drying and absorping of the desiccant. Does it tend to powder or change in physical characteristics?

Rush: So did we. The answer is no. At least as far as we can tell at the present time. Hopefully, we'll know more after we get through. There might be some people here from Cargocaire and so on. This type of drying wheel has been in business for a long, long time. Cargocaire and Wing have long experience. Many of the missile silos have had their humidity controlled by this type of a device.

There is a water wash on one side while on the other side you're going to have some kind of a screen to take out large particulates. If you will just remember for half of its cycle, where air with a linear velocity of 200 feet per minute impinges on one face, however over the next 2 1/2 minutes, there is a linear velocity of 200 feet per minute going the other way. We have seen no evidence of any kind of buildup, at least under the conditions we're operating. What this is going to do, how severe this is going to be, in an actual operating system, I can't tell you. I have however talked to the people who perform humidity control for dry ship holds for example, with some of the foulest atmospheres that have hit that thing and they seem to last for years.

Beckman: One or two more questions, short ones. If there are none, we won't ask again and call it quits and thank you.



MICROCOPY RESOLUTION TEST CHART

SESSION V - RANKINE CYCLE

Session Chairman: Harold Horowitz

Session V. Rankine Cycle - Burriss

SOLAR-POWERED RANKINE CYCLE COOLING SYSTEMS

William L. Burriss

The Garrett Corp.

Introduction

Solar-powered systems for building air conditioning require (1) a thermodynamic cycle that will give good performance at the relatively low temperature levels provided by low-cost solar collectors, and (2) equipment suitable for low-cost production and long-life operation with minimum maintenance.

This paper will discuss how the Rankine cycle system is able to meet these requirements and provide high system performance over a broad range of design conditions. The key to this approach is the turbomachinery technology that has been developed at AiResearch for a wide variety of applications. This technology already has been applied to the problem of diesel engine supercharging for the mass production of similar type turbomachinery (300,000 units per year present production rate). As will be discussed, the turbocompressor required with a heat-powered Rankine cycle system is simple in design and should be suitable for low-cost production.

System Description

Figure 1 shows the single-fluid heat-powered Rankine cycle cooling system using turbomachinery. The system is split into two loops, one a conventional Rankine power cycle with a turbine that drives a compressor in a conventional vapor refrigeration cycle. The two loops use the same fluid and share a common condenser. The preheater is an option that will be used for the higher temperature systems. The system also may include an alternator or motor on the turbine shaft to provide an auxiliary electrical output or input as additional options.

A number of different fluids can be used in these systems. Factors involving cycle performance, fluid stability at the operating temperature level, and cost will be involved in fluid selection. R-11 and R-113 show good performance and excellent stability characteristics in the 300^0 to 400^{0}F range. It has been indicated that R-114 is suitable up to 600^{0}F. The high-temperature organic working fluids developed for Rankine power systems represent other possibilities.

In the single-fluid system, shaft seals can be eliminated and the turbocompressor can be operated on fluid bearings. Elimination of the lubricant from the working fluid by use of fluid bearings avoids any potential fouling problem in the boiler. Furthermore, the fluid bearings have unlimited life. Elimination of dynamic external shaft seals minimizes refrigerant leakage from the system. These features result in a system that should have a very long and maintenance-free life.

Performance Characteristics

Figure 2 shows the effect of cycle boiling temperature on coefficient of performance for representative conditions. Coefficient of performance (COP) is defined here as the refrigerating effect per unit heat input to the cycle. The performance incentive for use of higher temperature and a preheater is graphically illustrated in Figure 2.

It is preferable to use a collector design that provides a higher boiling temperature. A substantial reduction in collector area is shown in Figure 3 for the higher temperature. In addition, the size of the condenser will be reduced by approximately one-half. Of course, high-temperature collectors are not practical for all installations. Consequently, low-temperature systems will be used, particularly for the lower ratings, where the complexity of the high-temperature collector cannot be justified.

Performance of low-temperature Rankine cycle systems is sensitive to condensing temperature, as shown by Figure 4. The performance gains obtained by reducing the condensing temperature must be balanced against the costs associated with a cooling tower, evaporative condenser, or other means required to provide the reduced condensing temperature.

The cycle performance tradeoff for evaporator design is shown in Figure 5. Some idea of the cycle performance as a heat pump can be gained from this chart, since heating COP is equal to cooling COP plus one. Like all vapor-cycle heat pumps, a reduction in heating capacity will be obtained with decreasing ambient temperature. In this case, however, it will hold up better than an electrically driven heat pump, since the system includes a power cycle as a part of the heat source.

Figure 6 shows the effect on performance of component efficiency and working fluid pressure drop in the heat exchanger. Turbocompressor product efficiency of 0.56 is readily attainable with good design. The turbocompressor is lightly stressed, simple in design, uses inexpensive materials, and should be suitable for low-cost mass production.

Turbocompressor

The turbocompressor is the only unique or novel component in the system. Figure 7 shows a turbocompressor developed by AiResearch for a heat-powered Rankine cycle cooling system. This system user R-11 and operates at a design of 230°F boiling temperature and a 147°F condensing temperature. The turbocompressor operates at a nominal 50,000 rpm and provides a rated system cooling capacity of 5 tons.

Mechanical simplicity of the design is apparent from Figure 8, which shows the disassembled turbocompressor. The turbocompressor has a single rotating shaft supported by gas bearings, containing a radial-inflow turbine at one end, and a two-stage radial-flow compressor at the other end. It should be emphasized that this is a prototype design and that considerable design simplification to reduce manufacturing cost is possible. For example, a single-stage compressor can be used for a system designed for a lower condensing temperature.

Figure 9 shows a closeup view of the rotors. The compressor rotors are approximately 2.25 in. in diameter; the turbine rotor has a 2.75-in. diameter. These aluminum alloy rotors are lightly stressed at the design 50,000-rpm operating speed.

Conclusions

In summary, it is concluded that the heat-powered Rankine cycle cooling system can be designed to operate over a wide range of design conditions and will be strongly competitive with absorption cycle systems. Two basic types of heat-powered Rankine cycle systems are envisaged for solar heat sources:

(1) A low-temperature cycle designed to operate at boiling temperature under 200°F with flat plate type solar collector.

(2) A high-temperature cycle that will be designed to operate at boiling temperatures on the order of 600°F with concentrating type solar collectors.

The first type of system may see more widespread usage because of its suitability for home air conditioning over an extensive geographical distribution range. The second may be restricted to relatively large systems and locations in the southwest areas of the country.

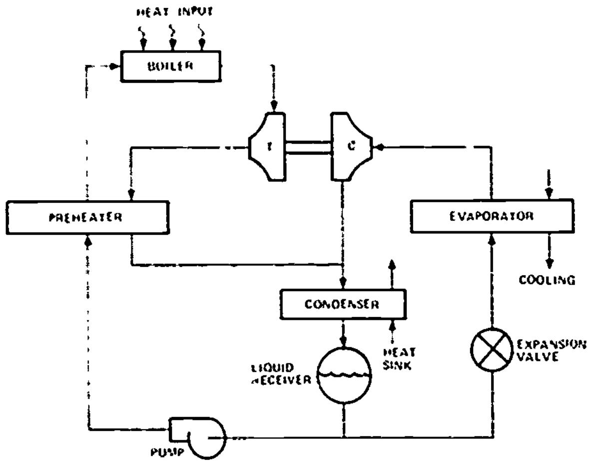


Fig. 1. Heat Powered Rankine Cycle Cooling System.

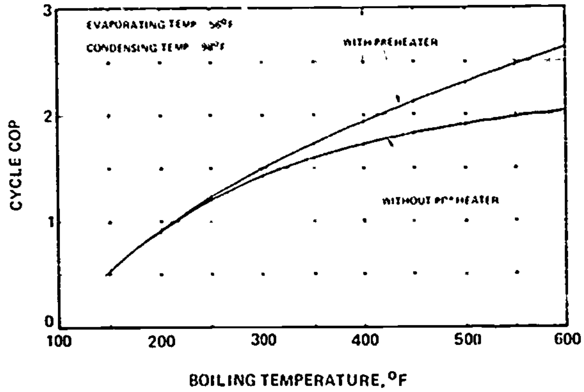


Fig. 2. Typical Effect of Cycle Boiling Temperature on C.O.P.

	SOLAR COLLECTOR TYPE	
	FLAT PLATE	PARABOLIC TROUGH
COLLECTOR EFFICIENCY	0.40	0.60
CYCLE BOILING TEMPERATURE °F	160	600
CYCLE COP	0.6	2.6
COLLECTOR AREA SQ FT TON	13.	18

Fig. 3. Typical Effect of Collection Temperature on Collector Size.

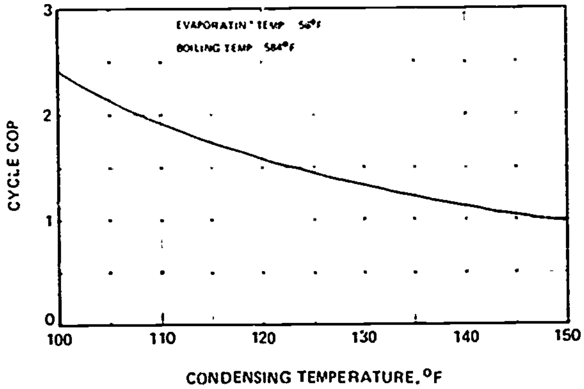


Fig. 4. Typical Effect of Cycle Condensing Temperature on C.O.P.

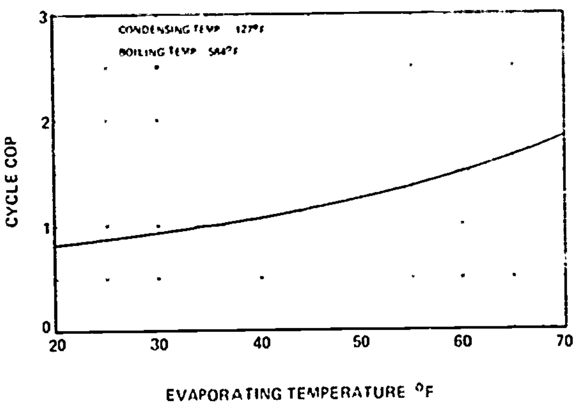


Fig. 5. Typical Effect of Evaporator Temperature on C.O.P.

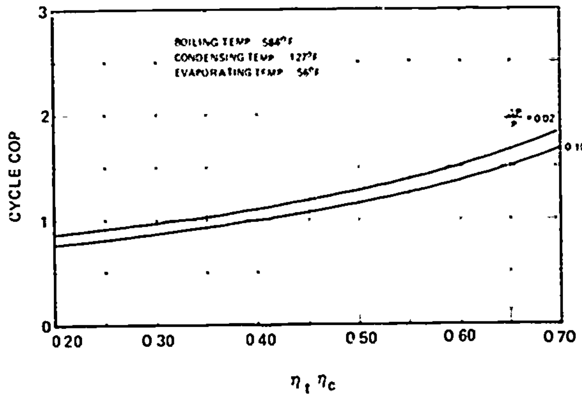


Fig. 6. Typical Effect of Component Efficiency and Working Fluid Pressure Drop on C.O.P.

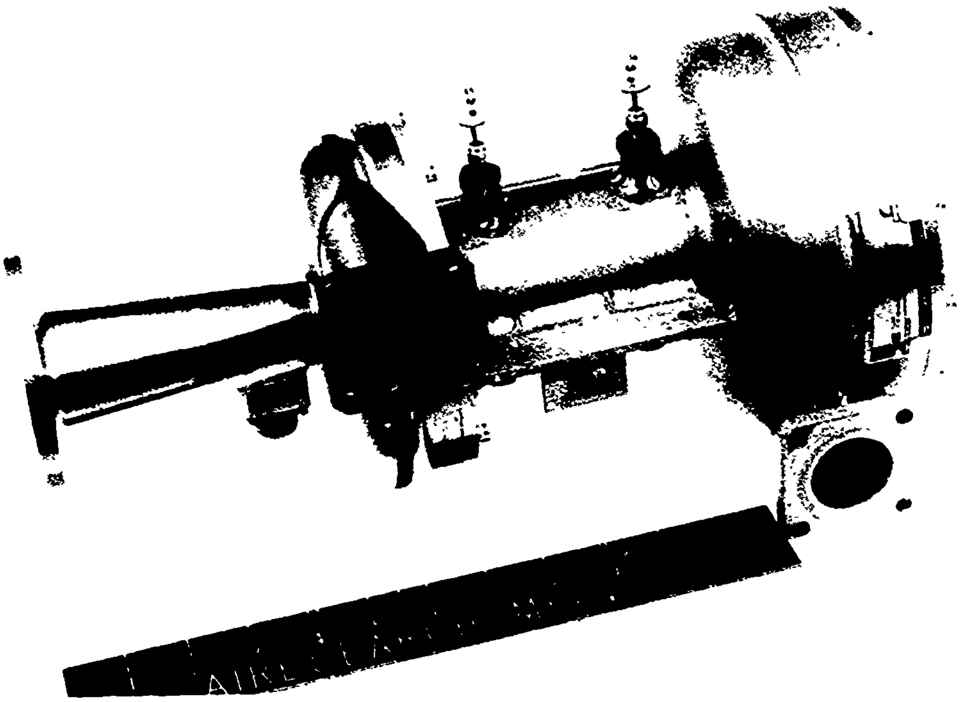


Fig. 7. AiResearch Turoocompressure for Rankine Cycles.

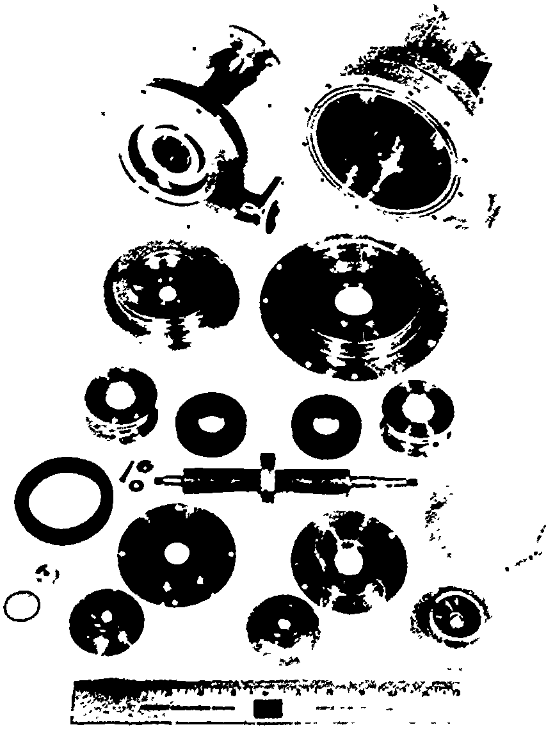


Fig. 8. Turbocompressor Components.

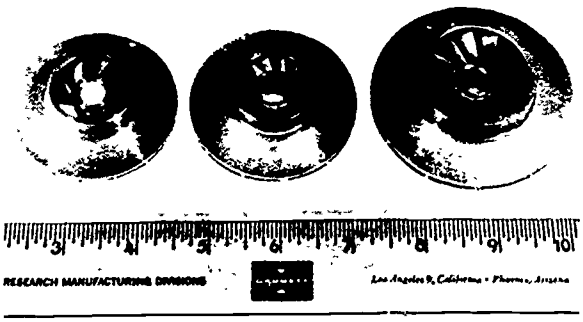


Fig. 9. Rotor Closeup.

Session V. Rankine Cycle - Curran

SOLAR RANKINE CYCLE POWERED COOLING SYSTEMS

Henry Curran

Hittman Assoc.

This presentation covers preliminary work on a recently awarded NSF contract. The project objective is to study the feasibility of using the Rankine cycle to convert solar thermal energy to mechanical energy, which is to be used to drive a compression refrigeration machine for the cooling of buildings. This is a rather specific application; heating or other ancillary possibilities for solar energy are not included. In a real system the solar collector would have to be integrated with other requirements such as space heating and water heating.

The specific tasks involve determination of the characteristics of Rankine cycles and other system components, and evaluation of the total system. Rankine engines which are of a small size and capable of operating at low temperatures will be of particular interest. The total system evaluation will not be an optimization, but primarily a determination of the overall conditions for feasibility. The Rankine engines under consideration include reciprocating, turbine and rotary engine expanders. Operational characteristics of interest are the working fluid, the maximum temperature, the condensing temperature, the mechanical load, pump work, fan work, service life, and costs.

Figure 1 shows a generalized system, indicating the possible components which might be considered in a Rankine cycle type system for space cooling. The solar collector has an energy input rate, $\dot{Q}s$, which is indicated schematically as a function of diurnal time. The cooling load consists of heat which is received from the space to be cooled. The cooling load rate, $\dot{Q}_L$, is also indicated with the respect to diurnal time. For a particular system an average overall COP may be defined as the ratio of the load rate integral to the solar energy input integral.

Various storage units are indicated, not all of which would be used in any one system. Dynamic storage between the Rankine cycle expander and the vapor compression refrigeration compressor might be, for example, a super fly-wheel. Possibilities for driving the system when there is no sunlight include an auxiliary thermal energy input to the Rankine cycle, or an auxiliary electric energy input to the vapor compression refrigeration compressor. Various trade-offs are possible here in terms of system capacity and storage capacity. For example, the peak cooling load could be taken care of by a low-temperature storage unit if the vapor compression unit were operated continuously at an average load value. The storage unit would take care of the diurnal variation and allow the use of a smaller capacity refrigeration unit for the 24 hour cycle. Additional storage could be added to take care of a cloudy day following a sunny day. However, this would increase the capacity of the vapor compression refrigeration machine, so that on a sunny day it could store cooling capacity for use on a cloudy day. The result of this is that, if the cloudy day does not occur, there is excess capacity in the vapor compression machine. Similar considerations can be made with regard to the high temperature thermal energy storage in its interaction with the solar collector. The question here would be whether or not to use more storage than would be required to cover the diurnal cycle. Additional energy storage to take care of a cloudy day following a sunny day requires that the solar collector be proportionately larger. If the cloudy day does not occur, then the solar collector is unnecessarily large for that particular point in time.

Figure 2 indicates the auxiliary energy alternatives when solar energy is inadequate. A local fuel input could be used to drive the Rankine cycle at some efficiency η_{RC}. The alternative is a fuel input into a power plant which delivers energy at a combined plant and transmission $\eta_P \eta_T$, efficiency to an electric drive. Assuming a value at 0.31, and allowing for a fairly high efficiency for the electric motor, η_M might be about 0.3. From the standpoint of energy conservation the choice would be on the relationship between η_{RC} and η_M. Assuming $\eta_M = 0.3$ the preferable alternative when $\eta_{RC} > 0.3$ is the local combustion of fuel. For $\eta_{RC} < 0.3$ the preferable alternative is the electric drive. Of course, the various fuel alternatives must also be considered in the analysis of auxiliary energy inputs.

Theoretical energy calculations provide insight into the attainable values of η_{AC}. Figure 3 shows the Carnot efficiency as a function of the upper and lower temperatures. Assuming an upper temperature at 250°F, which is quoted for some flat plate solar collectors, the Carnot efficiency at 90°F lower temperature, is on the order of 0.23. In a real system, of course, the efficiency would be much lower than this. Using water as a working fluid the ideal Rankine cycle efficiency for the same temperatures is about 0.08. This is one of the reasons why water is not an ideal choice for a low temperature Rankine cycle system.

Using an organic working fluid, such as R114, the ideal Rankine cycle efficiency, with regeneration, is about 0.19 for the 250°/90° temperature. Real R-114 cycles will have efficiencies much lower than this ideal value.

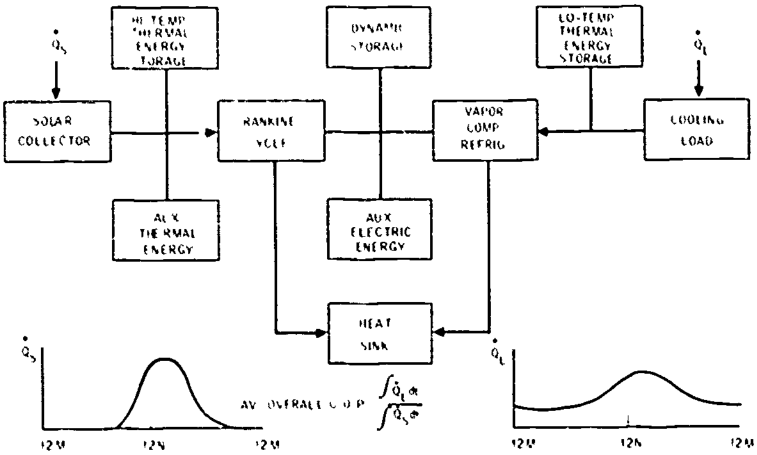


Fig. 1. Generalized Solar-Powered Cooling System Using Rankine Cycle.

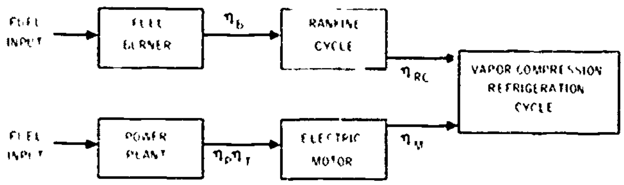


Fig. 2. Auxiliary Energy Alternatives when Solar Energy is Inadequate.

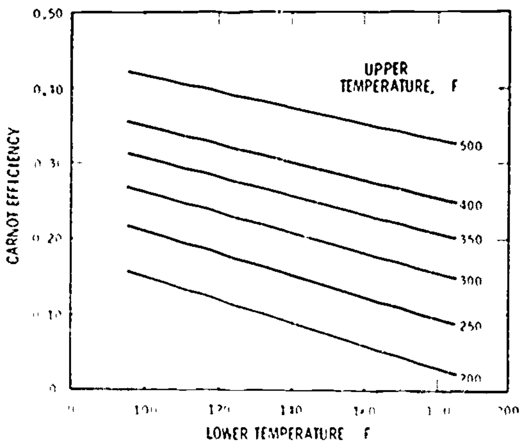


Fig. 3. Effect of Upper and Lower Temperatures on Carnot Efficiency.

Session V. Rankine Cycle - Biancardi

NEEDED RESEARCH ON SOLAR RANKINE SYSTEMS

Frank R. Biancardi

United Aircraft Research Laboratories

Background

United Aircraft's activities in Rankine cycle systems began approximately ten years ago and I'd like to describe how some of that work is related to the Solar-Power Turbocompressor System concept I'm advocating today. I believe that the concept of using Rankine cycles in conjunction with solar power is possibly more mature than many people at this conference are aware of.

UA work in Rankine cycles and specifically in Rankine cycle thermally-powered air conditioning systems began (as indicated in Figure 1) with a request in 1963 by Columbia Gas Service System Corporation to look at new and novel ways of using natural gas to provide air-conditioning. The motivation for this work at that time was to encourage the sale of natural gas during the summer in order to even out the year-round sales profile. During this work UARL undertook studies to compare fluids for use in Rankine cycle air-conditioning systems and some preliminary component design and evaluation work. This activity extended over the next couple of years under corporate funding during which time extensive design and cost analyses were undertaken. Some corporate work on bearing tests for our turbocompressor concept were also performed at the Hamilton Standard Division (HSD) of UA. Finally, a demonstration unit was built by HSD and performance and control system testing of the unit was performed. Estimates of the total development costs were also made and I might note that the figures were not $100,000 to $1,000,000, but more like several million to bring such a product to the market place and have it be successful.

During this time UARL also evaluated a number of waste heat applications. Waste heat turns out to be a very interesting area for Rankine cycles because of the unique characteristics of many organic working fluids which make them suitable for use at low peak system temperatures. Many applications were found such as the petrochemical and ammonia plants which have abundant low-temperature waste heat sources from which useful power to operate refrigeration systems or to produce electrical energy could be generated.

In early '69 a summary of the program activities in air-conditioning was presented to ASHRAE. Finally, geothermal applications and a number of other areas which could use Rankine-cycle systems were studied. For example, enormous quantities of power using fluorocarbon working fluids (i.e., the Freons) can be provided using a Rankine-cycle bottoming system and this may be an application that will come along in the next five to ten years.

Air-Conditioning Concepts

Figure 2 shows some of the concepts that were evaluated during our early studies of thermally-powered air conditioning systems. Some of these same concepts are being advocated again for use with solar energy. Our evaluations included an extensive review of absorption systems, both of the conventional NH_3-H_2O and LiBr-H_2O and other types. Although absorption systems provide an opportunity for heat exchanger manufacturers, our study indicated that a unique thermally-driven class of systems would be the so-called double-loop systems. There are two basic types of double-loop systems; one which uses a reciprocating expander-compressor or a turbine and compressor, and the other which uses an ejector to provide compression for the cooling system. A basic problem with an ejector double-loop system is that an ejector is not as efficient as a compressor. Although substantial development funds have been spent by various organizations in an attempt to improve ejector efficiency these efforts have never been too successful. Therefore, double-loop systems will require the use of a reciprocating expander-compressor or turbomachinery to achieve high efficiency levels.

Figure 3 shows a very simplified diagram of the turbocompressor air-conditioning double-loop system. There are two loops; one is the power loop which consists of the Rankine-cycle power generation system and the other is the cooling loop which consists of the vapor compression refrigeration system. Hot fluid from the collector/storage system is used to vaporize the power loop working fluid which is expanded in the turbine to produce work to drive the compressor. The overall motivation in devising the turbocompressor system has been to provide a simple, low cost, low maintenance system. If a small reduction in performance was required to reduce cost or increase reliability this was generally an acceptable compromise, since the major competition is an electric driven-vapor compression system which represents a very low-cost target. During our study various means of reducing costs yet providing reasonable performance were examined. For example, the use of a single working fluid in both the power loop and the cooling loop was selected even though this did not provide the highest performance system, since it results in reduced costs. With only one fluid in the system, elaborate seals are not required and two separate loops with receivers, fill-lines, etc. are not necessary. The use of a regenerator was also evaluated and it was decided that the added complexity was unwarranted in the system, even though a modest performance improvement is possible.

The coefficient of performance (COP) of double-loop system can be determined in a simplified fashion by using the ideal efficiency of the power generation cycle, the ideal COP of the refrigeration cycle together with the estimated turbine and compressor component adiabatic efficiencies ($\eta t, \eta C$) as shown in Figure 4. If the system includes a fired-burner the burner efficiency of which (ηb) should also be included. However, for solar energy applications this is equal to unity.

Working Fluid Selection for Double-Loop Systems

Selection of the working fluid for a residential or industrial solar-powered air-conditioning system requires consideration of many factors, including limits of working fluid chemical stability, maximum system pressure levels and hence safety and design code requirements, achievable component performance levels and overall system performance and cost. The coefficient of performance of double-loop systems using common low-cost refrigerants are shown in Figure 5 as a function of maximum system pressure (hence turbine or expander inlet pressure) and working fluid temperature. Common low cost refrigerants were considered as the system working fluid in order to minimize overall system cost and also to reduce development costs. The highest temperature values for the refrigerants indicate the maximum levels to which these materials should be exposed in the absence of oil to avoid rapid decomposition and corrosion in the system. The limits are based on extensive analytical and experimental data provided to UA by the refrigerant suppliers. The probable levels of reciprocating expander-compressor and turbine-compressor product efficiencies that could be achieved with minimum development are also indicated in Figure 5. For a residential application requiring 3 to 5 hp expanders or turbines only R12 and R22 appear suitable for use in a reciprocating machine, while water, R114, R113, R21 and R11 would be suitable for a turbocompressor unit. Water, however, would not be ideal for low-cost applications, in spite of the high COP levels. The high pressure ratios required in the turbocompressor when using water result in a multi-stage turbine and a multi-stage compressor to achieve good performance levels and the system becomes too costly to manufacture. For small-to-moderate tonnage double-loop systems the common refrigerants (Freons) are far superior fluids, especially R113, R11, R21, as indicated in Figure 5.

These refrigerants provide the highest performance levels even though a $\eta t \times \eta c$ product efficiency of 50 rather than 60 was selected in the comparison studies. Even at operating temperatures of 200°F a COP of about 0.3 can be achieved with these fluids. Because of the high specific volume characteristics of R113 and R11, they appear to be the best choices for a residential solar-powered system. However, studies at UA have shown that R11 and R114 would be attractive candidates for larger capacity turbocompressor air-conditioning systems (i.e., several hundred tons or above) for commercial applications.

E.I. Dupont, Inc. did very substantial testing for us over a range of temperatures which showed that operation at 300-400 F would be possible for selected refrigerants if oil and water were kept out of the system. Even at lower temperature conditions, oil should be kept out of the system which further indicates that none of the concepts using reciprocating expanders would be too satisfactory. If you do use oil there is the problem of breakdown. In a double-loop system using a single working fluid you can generally avoid using oil if a hydrodynamic bearing using the working fluid as the lubricant were employed.

A lot of discussion has taken place as to the performance level available with a maximum system temperature of 200 F, the level which would be available from today's low cost flat-plate collectors. Figure 5 shows that a COP of about 0.3 is possible with R113 and R11 at a specified condenser temperature of 125 F. Although this condenser temperature would be suitable for air cooling, much lower temperatures are possible with water cooling. Figure 6 shows the performance improvement with lower condenser temperature and also with improved turbocompressor product efficiencies ($\eta t \times \eta c$). A system has been run at HSD using available components modified to run with Freon 114 which had a $\eta t \times \eta c$ product approaching 50%. Subsequent studies indicated a turbocompressor product efficiency of 55% could be achieved with further development and levels as high as 65 are feasible. Figure 6 shows that with the highest turbocompressor product efficiency and a 110 F condenser temperature a COP of 0.6 is possible. This would be very competitive with the performance of an absorption system and we believe would make the system competitive on initial cost basis as well.

Improvements in collector maximum temperature capability as shown in Figure 7, would improve the system performance and result in smaller collector per ton of refrigeration requirements.

The type of turbomachinery required for the double-loop system is very similar to that which has already been built by HSD for various aircraft environment. control systems as shown in Figure 8. An artist's drawing of the turbocompressor design that might be utilized in a developed system is shown in Figure 9. Estimates of the turbocompressor product efficiency for this design are approximately 55%. The design incorporates a single-stage compressor directly connected to a single-stage turbine. Each unit has an impeller diameter of approximately three inches. A hydrodynamic journal bearing would be used in the unit and based on earlier tests, I mentioned we're confident that we could build a unit like this at very competitive costs. The 3-ton turbocompressor test system built by HSD and shown in Figure 10 used off-the-shelf turbine and compressor wheels and operated for several hundred hours.

The turbine was actually designed to run on air but was run with R114 which was the fluid used for the original compressor. A vapor generator heated by steam provided R114 at about 275 F to the turbine inlet although other temperature conditions were also examined.

A motor driven pump shown in Figure 10 was used to circulate the R114 in the power loop. Figure 11 shows another view of the test unit. Although R114 was used in both the power and cooling loops, separate condensers were utilized.

A selling price comparison performed by Hamilton Standard indicated that the turbocompressor system would be competitive with electric-driven systems, air-conditioning, and absorption equipment. Figure 12 summarized some of the advantages of the turbocompressor system; most important of which is good performance with low collector temperatures. It has increased performance potential both by going to higher maximum system temperatures and by improving the performance of the turbine and the compressor. You can use a common low-cost, non-toxic refrigerant like R11, R1 3, R114. The best fluid is a function of how much power or how much air-conditioning you want out of the unit. An other advantage is that one working fluid can be used in both loops and that's part of the secret to getting low cost because we have one condenser, no seals, and the unit can be hermetically sealed. Capital costs should be competitive and there are a lot of alternatives for providing heat with the system. Finally, concept feasibility has been demonstrated at higher temperatures using the HSD test unit.

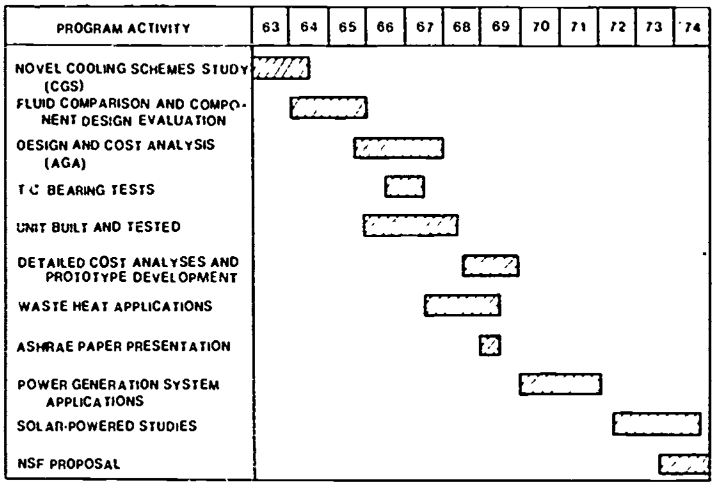


Fig. 1. Rankine Cycle Air Conditioning Background

Fig. 2. Thermally-Powered Air Conditioning Systems

1. ENGINE-DRIVEN VAPOR COMPRESSION SYSTEMS
   - OTTO-CYCLE GAS ENGINE
   - BRAYTON CYCLE ENGINE
   - STIRLING-CYCLE ENGINE
   - FREE-PISTON ENGINE
2. ABSORPTION SYSTEMS
   - AMMONIA-WATER
   - LITHIUM BROMIDE-WATER
   - OTHER ABSORBENT REFRIGERANT COMBINATIONS
3. DOUBLE-LOOP SYSTEMS
   - EJECTOR POWERED
   - RECIPROCATING EXPANDER COMPRESSOR OR TURBOCOMPRESSOR

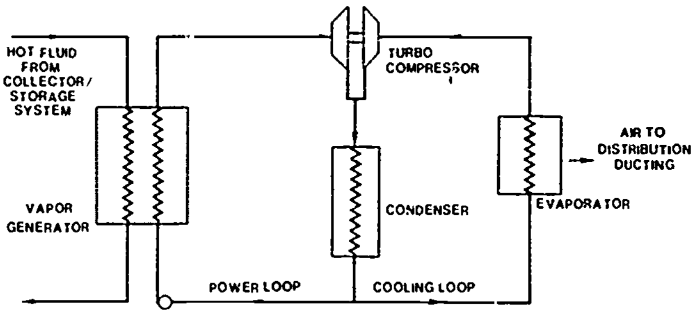


Fig. 3. Turbocompressor Air Conditioning System

$$COP = \eta_b \eta_c \eta_t \eta_{ths} COP_{isen}$$

Fig. 4. Performance of Mechanical Expander-Compressor Systems

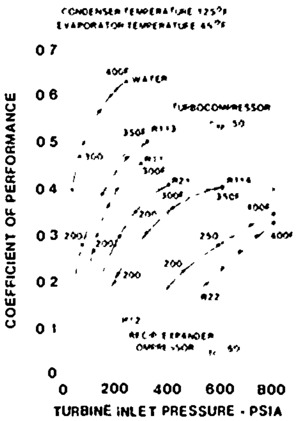


Fig. 5. Working Fluid Comparison

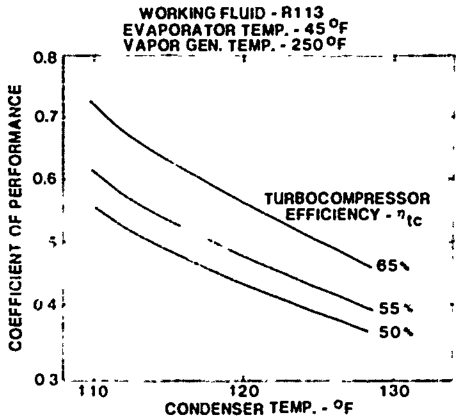


Fig. 6. Cooling System Performance

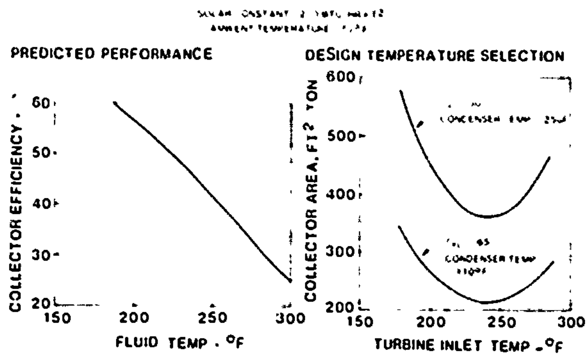


Fig. 7. Solar Collector Characteristics

Fig. 8. High Speed Wheels

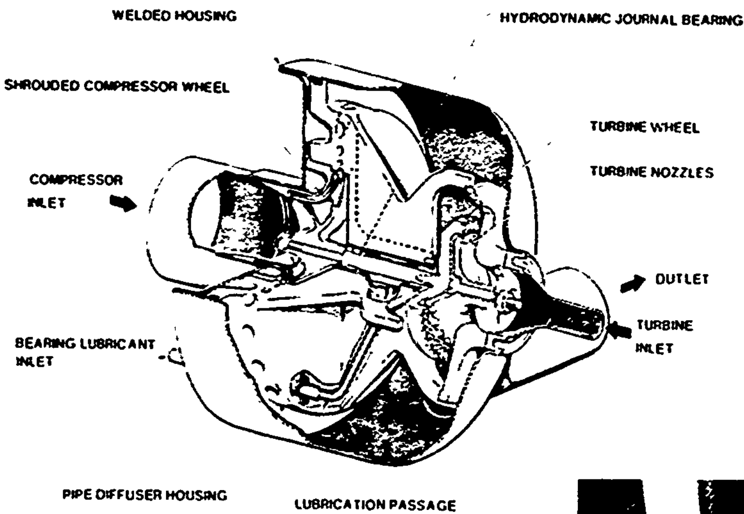


Fig. 9. Turbocompressor Unit Design

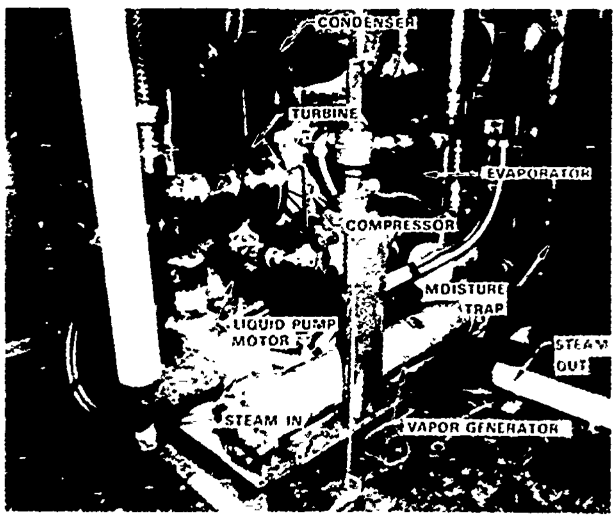


Fig. 10. Turbocompressor Test System

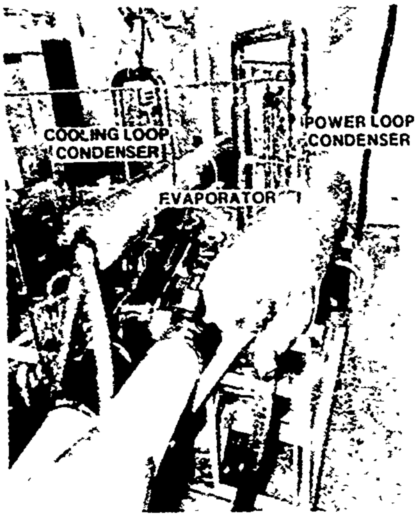


Fig. 11. Turbocompressor Test System

- GOOD PERFORMANCE WITH LOW COLLECTOR TEMPERATURES
- COMMON LOW-COST NON-TOXIC REFRIGERANTS
- ONE WORKING FLUID IN BOTH LOOPS
- COMPETITIVE COSTS
- HEATING READILY PROVIDED
- INCREASED PERFORMANCE POTENTIAL
- POWER GENERATION POSSIBLE
- VERSATILE CONFIGURATIONS (SUPPLEMENTARY ELECTRIC DRIVE)
- CONCEPT FEASIBILITY DEMONSTRATED

Fig. 12. Advantages of Turbocompressor System

SOLAR RANKINE POWERED COOLING SYSTEMS

Jerry Davis

TECO

Rather than making a broad fluid survey and ideal cycle calculations as previous speakers have done, I'd like to concentrate on a specific analysis of a two fluid system organic Rankine cycle for solar cooling. Figure 1 shows the Rankine cycle for the shaft power production for the reciprocating expander. R114 seems to be one of the better choices. For a turbine expander perhaps another fluid such as R113 is a more appropriate choice. But in any case, using R114, let me just trace through the cycle on a pressure enthalpy diagram to show what goes on. Fluid enters into the boiler, subcooling is removed, boiling occurs, then there is a little bit of super heat imparted to the fluid. It is expanded through either a reciprocating or turbine expander. There is a small amount of super heat at a typical condensing temperature which can be utilized to make some relatively small improvement in the overall cycle efficiency by desuperheating the exhaust gas and regeneratively heating the boiler feed. The fluid is then condensed, pumped back to boiler pressure through the liquid side of the regenerator and into the boiler.

Figure 2 indicates what the power cycle efficiency would be as a function of both water outlet temperature and condensing temperature. I'd like to point out in this analysis that a component efficiency of 72 for reciprocating expanders have been demonstrated in the laboratory and in operational systems. A feed pump efficiency of 80 or better has also been demonstrated. Pressure drops have been estimated for the system and the power efficiency cycle is therefore not directly comparable to some of the theoretical cycle analyses that we've seen earlier. As our best estimate of a real net shaft power output, at a typical boiler outlet temperature of 212 degrees F and 120 degree condensing temperature we get a little over eight percent.

Figure 3 indicates an overall COP at the 212 degree boiler outlet temperature and 120 degrees condensing temperature (which of course would be an air cooled condenser) using a conventional refrigerant cycle in a completely separate loop with R22 and a compressor efficiency of 72 . An overall COP of a little over 0.3 was obtained for this analysis.

Figure 4 indicates a somewhat better choice of refrigerant for these particular cycle conditions, R142B, I believe an Allied Chemical fluid, using an identical compressor efficiency to what was used for the R22 analysis at the 212 degree boiler outlet temperature, 120 degree condensing temperature. Something like 0.36 is realized for an overall COP. Of course, at some of the conditions that have been discussed of some of the absorption machines with a 200 degree solar collector and perhaps an 80 degree condenser temperature, COP's would be on the order of 1.3. This might be more typical of a water cooled condenser with 72 degree cooling water available.

Figure 5 indicates the comparison of a variety of refrigerants for the refrigeration cycle. Figure 5 includes R142B, an azeotropic mixture of R31 and R114, and R22 and R114 alone. And the effect on COP is significant enough that one certainly has to consider what an optimum refrigerant ought to be for the kinds of conditions that we're talking about operating at.

We have analyzed the performance of single fluid systems. We've operated a single fluid system, reciprocating machines using R114 in both the power mode and the refrigeration mode and it's apparent there is no single working fluid available which maximizes the performance of both the power and the cooling cycle. A dual fluid system invariably results in the highest overall COP which can be obtained and will probably result in lower overall cost when one considers the entire system, including the solar collector, than any single fluid system that one can imagine. So, we have given a primary emphasis to the dual fluid system.

Figure 6 indicates in a little more detail the design point for the system that we've been looking at. The power cycle fluid is R114, with a 212 degree outlet temperature which does include about 7 degrees of super heat, and an outlet pressure of about 200 PSIA. The expander in this particular analysis was a 15 cubic inch displacement reciprocating unit operating at a speed of 1,800 RPM and generating a net shaft power of a little in excess of three horse power at an overall efficiency of 72%. I might say in this regard that in considering the reciprocating versus the turbine expander, there are advantages and disadvantages for both types. The reciprocating machine would probably be a little less sensitive in its overall efficiency to variation in inlet pressure than a turbine would be. However, the turbine falloff in efficiency operating at off-design conditions is really not too profound, but in the reciprocating expander using a variable intake valve for admitting the working fluid to the cylinders, it is possible to maintain very close to the design efficiency of the unit over a pretty broad pressure and temperature inlet range. As I said, the overall net efficiency of the cycle is on the order of eight percent.

The cooling cycle shown previously using 142B as the working fluid for the conditions of a 123 condensing temperature and a 45 degree evaporating temperature, gave an overall net COP of 4.5 and the combination for these conditions of the power and the refrigeration cycle gave an overall COP of 0.36.

Figure 7 shows one of the two cylinder reciprocating expanders that has been designed and manufactured and operated at Thermo Electron for units of this type. I believe they have now seen some thousands of hours of operation. Its a relatively inexpensive low speed machine. It does incorporate a shaft seal at the output shaft. We have operated shaft seals of this nature. It's a double seal basically with a buffer pressurizing the space between the interior of the system and the ambient so that any leakage in the system, is not leakage of working fluid out to the atmosphere, nor leakage of atmosphere into the system under any conditions. Typical cost estimates for production for this kind of expander, and it is somewhat larger than the expander that would be needed in a three ton system, are on the order of two to four hundred dollars, in the vicinity of perhaps $100 per kilowatt. I might point out by the way, if one goes through a rather simple economic analysis assuming the value of electric power is in the order of 4¢ per kilowatt hour, it turns out that a break even point for capital investment is on the order of three to four hundred dollars per killowatt. This is, if the system can be purchased in this cost range, something in the neighborhood of $1000 for a system that gives a shaft output that can be utilized either for refrigeration or for electric power production, and that system costs in the neighborhood of $300 to $400 a kilowatt. That's a break even point for 4c per kilowatt hour, pretty close to the cost in the northeast today.

Figure 8 shows a turbine expander which we have been operating at Thermo Electron. This unit by the way was the result of a cooperative program between ourselves and the Barber Nichols Engineering Company. It's a 70,000 RPM machine, two inch plus diameter turbine wheel. It's internally geared down from the 70,000 RPM to an output speed of 3600 RPM. At 3600 RPM no problems have been experienced with respect to sealing an output shaft for a very long period of time with essentially zero leakage. This unit was designed for a full admission 30 horse power output, and operated in a partial admission mode at something like six horse power well below its full admission capability. Nevertheless, efficiencies of approximately 60 for the overall turbine plus two stage reduction gear box were obtained for this unit.

Figure 9 shows a three kilowatt engine generator package in the process of being assembled. Several of these units have been put together and operated. Two of them are presently at Fort Belvoir undergoing a variety of testing. This is a cube of about a little under three feet on the side, and it has got a net output of three kilowatts. The condenser unit is at the top, this is the reciprocating expander and a military version three kilowatt alternator. $350 a kilowatt for the equivalent of what would be required for a three ton air conditioning system is something which we are not quite at in the production costs, but estimates for what systems like this might cost are not all that far away. In todays cost structure, 4c a kilowatt hour, for power cost, we're within closer than a factor of two of being able to produce a machine which does meet the criterion of $350 a kilowatt at this power level.

Figure 10 shows the hardware for the organic Rankine cycle installed in a floor sweeper. This unit is operational and the unit has been in plants to maintain a very low levels of indoor pollution from operation of the organic Rankine cycle. The system itself has performed quite satisfactorily.

Figure 11 shows the six horse power organic Rankine cycle equipment installed in the rear of a personnel carrier. Three of these vehicles are in operation. Two with reciprocating expanders, and one with a turbine expander operational at a Japanese vehicle manufacturers facility undergoing evaluation for potential applications for small urban commuter vehicles.

The reason why I'm showing some of this hardware is to give you a feel for the state of the art technology of organic Rankine cycle systems. It wasn't too many years ago that there was quite a bit of talk about organic Rankine cycle systems, but not an awful lot of them running. At the present, several units have been built, and operated. As far as power generation with an organic Rankine cycle, for the kinds of source temperatures and sink temperatures that we're presently contemplating, the extrapolations from the kind of systems that have already been built are not really too profound.

Figure 12 is a view of a somewhat larger unit. This is an organic reciprocating expander for an automotive application. This is a 150 horse power unit which has been developed under the sponsorship of the Environmental Protection Agency. At the present time, two systems are being supported by EPA. A water system and an organic system at Thermo Electron for possible application in an automobile.

In conclusion, I would like to say that the application of the organic Rankine cycle to power production from a solar energy source, either as shaft power to drive a conventional refrigeration system or for electrical power production is quite near at hand. All that will be required is a couple of years of pretty hard and intensive study, experiment and evaluation and it's a cinch that competitively priced systems could be available in the relatively near term.

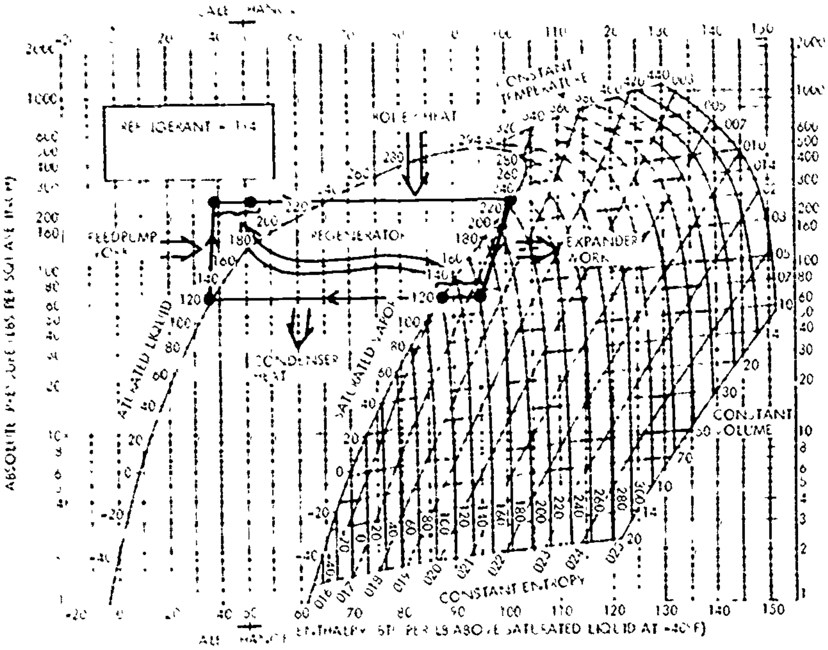


Fig. 1. Pressure-Enthalpy Plot of F-114 Showing Rankine Cycle with Regenerator

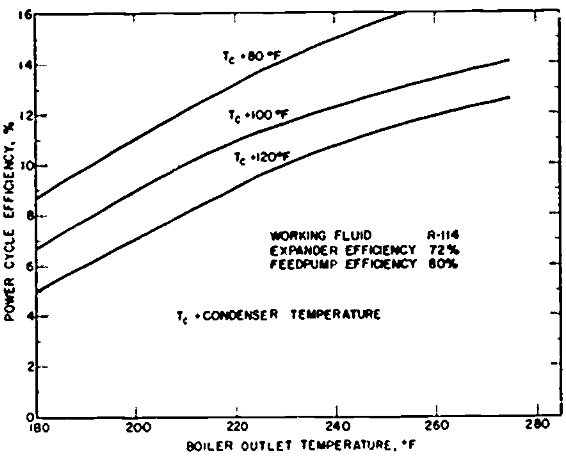


Fig. 2. Power Cycle Efficiency As a Function of Water Outlet Temperature and Condensing Temp.

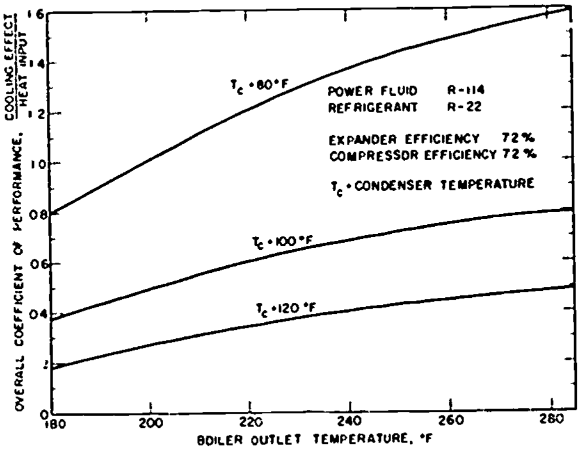


Fig. 3. Overall C.O.P. As a Function of Water Outlet Temp. & Condensing Temp. F-114/F-22

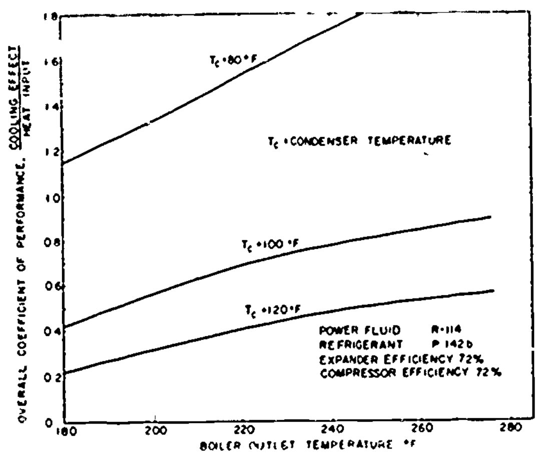


Fig. 4. Overall C.O.P. As a Function of Water Outlet Temp & Condensing Temp. F-114/F-142b

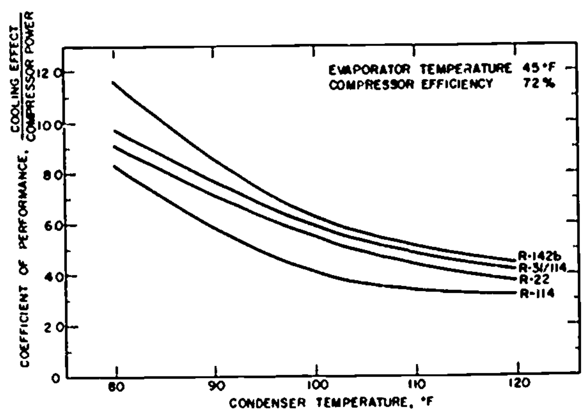


Fig. 5. Comparison of Various Freons for the Refrigeration Cycle

Power Cycle

Working Fluid — R-114

Boiler

Outlet Temperature	212°F
Outlet Pressure	205 psia
Heat Transfer Rate	98,920 Btu/hr

Expander (reciprocating)

Displacement	15.4 in³
Speed	1800 rpm
Horsepower (less feedpump)	3.15 hp
Efficiency	72%

Feedpump (reciprocating)

Working Fluid Mass Flow Rate (1800 rpm)	1785 lbm/hr
Overall Efficiency	80%
Power	0.33 hp

Condenser (power cycle)

Heat Transfer Rate	90,400 Btu/hr
Temperature	120°F
Pressure	63 psia

Efficiency

Rankine-cycle System Efficiency	8.1%

Cooling Cycle:

Working Fluid — R-142B

Evaporator

Temperature	45°F
Pressure	27.5 psia
Heat Transfer Rate	36,000 Btu/hr

Condenser (Cooling Cycle)

Heat Transfer Rate	44,000 Btu/hr
Temperature	120°F
Pressure	97 psia

Compressor

Efficiency	72%
Power	3.15 hp
Mass Flow Rate	525 lbm/hr

Cooling Cycle C.O.P

C.O.P.	4.47

Combined Cycle:

Heat Input	98,800 Btu/hr
Cooling Load	36,000 Btu/hr
Coefficient of Performance	0.365

Fig. 6. Design Point for System of Interest

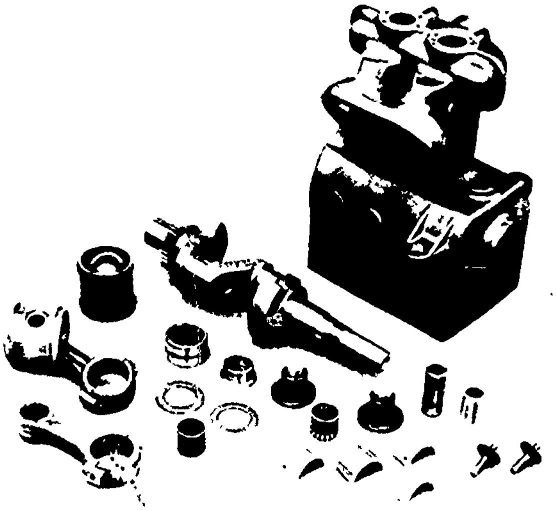


Fig. 7. Two-Cylinder Reciprocating Expander

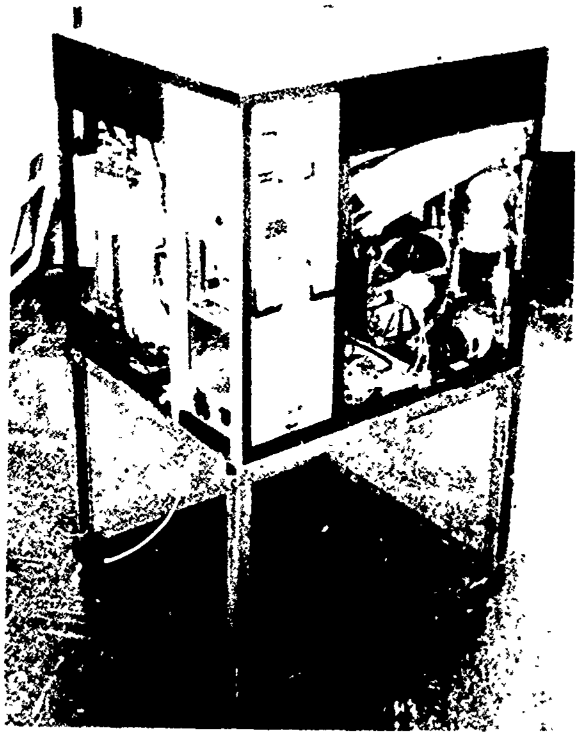


Fig. 9. Three Kilowatt Generator Package

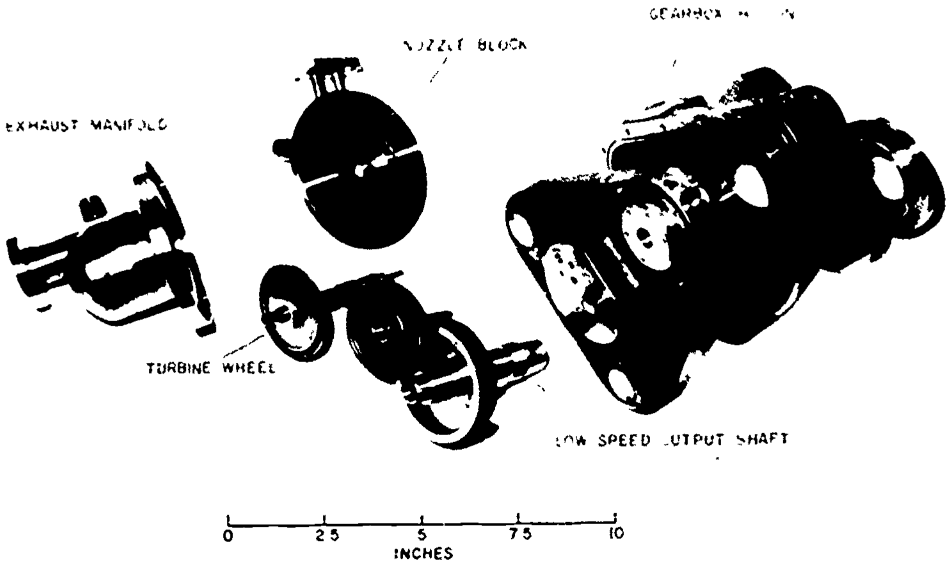


Fig. 8. Turbine Expander

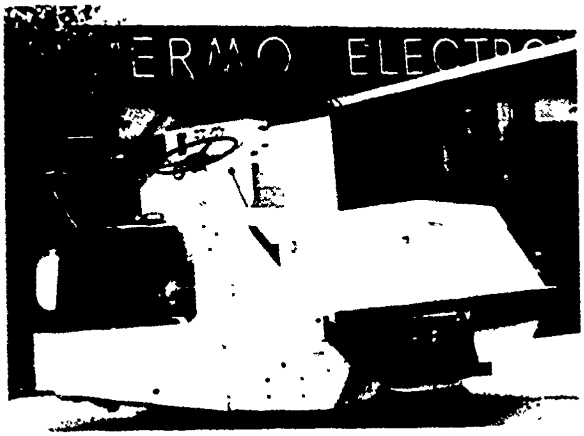


Fig. 10. Rankine Powered Floor Sweeper

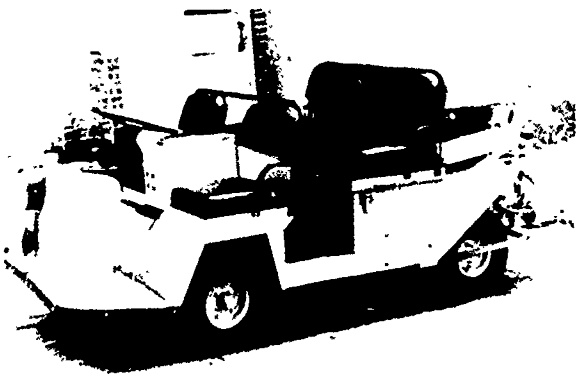


Fig. 11. Rankine Powered Personnel Carrier

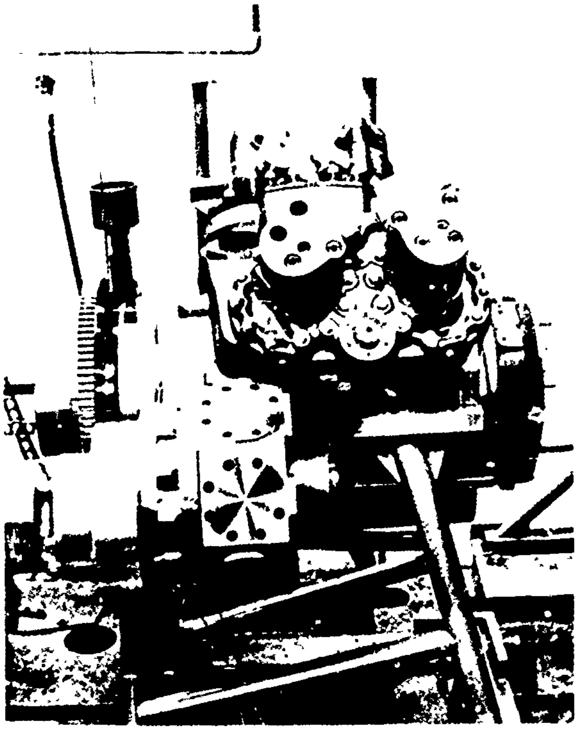


Fig. 12. Automotive (150 Horsepower) Rankine Cycle Engine

SOLAR ORGANIC RANKINE CYCLE POWERED THREE TON COOLING SYSTEM

Robert E. Barber

Barber-Nichols Corp.

Abstract

The development of a demonstration package supplying residential cooling and/or electricity via a solar heated Rankine Cycle is discussed. The three ton air conditioning-one kilowatt electric system employs a solar collector to warm flowing water which provides input heat to a low temperature organic (R-113) Rankine Cycle. Expansion through a high speed (~50,000 rpm) turbine-speed reducer drives an available R-12 refrigeration compressor and 3600 rpm motor-generator.

The design point solar collector water temperature is 215°F, providing an R-113 temperature at the turbine inlet of 200°F. With a water-cooled R-113 condenser purveying a condensing temperature of 95°F and a turbine efficiency design goal of 80%, Rankine Cycle efficiency (turbine shaft power divided by heat input to the working fluid) is 11.5%. An 85% efficient R-12 compressor yields an overall coefficient of performance goal of 0.71.

The project is jointly funded by Honeywell, Inc. and the National Science Foundation.

Introduction

The utilization of energy from the sun has reached an all time high. All indications point toward even greater solar usage in the future as a worldwide energy affluent attitude changes to one of energy consciousness. Most of the current solar applications involve the heating and/or cooling of buildings. The widespread usage of insolation for air conditioning purposes would substantially reduce summertime peak electrical power demands while conserving the dwindling supply of conventional fossil fuels.

Most solar cooling schemes employ absorption systems, some of which are described in Swartmann and Ha (1972) and in Williams et al (1958). The fact that an absorption refrigerator requires direct heat rather than mechanical input makes this concept well suited to operate in the solar regime. There are limitations with current absorption machines, though, among which are performance penalties at startup and a relatively narrow operational temperature band (175-200°F).

Another alternative producing air conditioning from incident solar radiation uses a conventional mechanical compression refrigeration loop powered by a solar-supplied, low temperature, organic Rankine Cycle (RC) (Sargent and Teagan, 1973; and Kirpichev and Baum, 1954). Certain characteristics of this method make it worthy of consideration as an alternative. Among these are its reliability, relatively wide operational temperature band and potentially low cost.

Organic Rankine Cycles have been under development for over 15 years. During this time three major developmental problems have frequently arisen. These are: a) working fluid thermal decomposition due to local boiler over-temperature; b) system instabilities emanating from control problems due to rapid changes in load or heat source; and c) mechanical problems stemming from valving and lubrication of piston-type expanders. At the same time significant advances have occurred in pump, heat exchanger, turbine expander, and speed reducer development areas. Fortunately the application of a Rankine power system to the realm of solar air conditioning and power production circumvents the three major RC development enigmas. The over-temperature problem area is bypassed since the solar heat source temperature is well below thermal decomposition limits of common organic working fluids (400^0F). Secondly, system instability problems are simplified since no rapid heat source changes will occur and the load is stabilized by the utilization of an induction motor. Since the motor will be connected to the residential electrical power supply it will draw power whenever a solar decline causes Rankine Cycle output to fall below air conditioning demand. Conversely, when RC power production exceeds AC demand, the induction motor generates electrical power while serving to prevent turbine over-speed conditions. Finally, the reliability, lubrication, and valving problems associated with piston expanders are not encountered with a turbo-expander.

System Description

The system described by this paper is one which provides three tons of air conditioning, one kilowatt of electrical power, or combinations of cooling and electricity whenever 11 gpm of 215^0F water can be supplied by a solar collector and 25 gpm of 85^0F cooling water is available. It was designed by Barber-Nichols Eng. Co. in support of Honeywell's effort to provide a mobile solar energy research laboratory. The laboratory also possesses heating capability developed by Honeywell which is not discussed herein. It is constructed on a trailer (see Figure 1) so that it might be transported to various parts of the country. In this way performance can be studied for a variety of climatic conditions. The Honeywell solar cooling-power generation system is composed of a Rankine Cycle (RC) subsystem and an absorption subsystem so that a direct performance comparison can be made. Within the RC portion is a Rankine power cycle and a compression refrigeration vapor cycle (Figure 1). The power-refrigeration package measured 39 x 41 x 47 inches and weighs 1400 pounds.

In the power cycle R-113 is pumped from a commercially available condenser by a magnetically coupled hermetic centrifugal feed pump through a regenerator to the boiler. From the boiler 200^0F vapor is admitted to a radial inflow turbine which provides power through a speed reducer to a conventional R-12 piston air conditioning compressor and/or to a motor-generator. Assembled and disassembled views of the turbine-gearbox are shown in Figure 2. After leaving the turbine low pressure vapor passes through the regenerator, an efficiency improvement device, and again into the condenser.

In the air conditioning (AC) portion R-12 is supplied from a 45^0F evaporator to a standard Carrier reciprocating compressor. Vapor at 125 psia leaves the compressor at 128^0F and enters the condenser, where the vapor to liquid phase change occurs. Expansion of the high pressure liquid leaving the condenser through a thermal expansion valve provides the evaporator with a mixture of 45^0F liquid and vapor. Forced room air circulation over the evaporator supplies the energy necessary to complete the R-12 vaporization process while providing 36,000 BTU/hr of room air conditioning. Figure 3 shows the test stand containing all RC and AC components. The refrigeration compressor has low oil pressure shutoff and high or low suction pressure shut-off controls which serve as safety devices to prevent evaporator freeze-up or compressor damage due to liquid injection.

The interface between solar and electrical power is accomplished via centrifugal clutch. During periods of partial or no solar energy input, electrical energy can be supplied to the AC compressor at 220 volts, 60 cycle AC, single phase. When air conditioning is not desired, up to one kilowatt of power can be generated, depending on the solar heat input.

Cycle Selection

Several power and refrigeration cycle fluids were considered for this solar application. Table I summarizes the comparative results for six RC and five AC fluids examined. The upper portion of Table I reveals that most fluids provided cycle efficiencies (η_c) between 9.5 and 10.5. for the turbine inlet temperature (T_0) and condensing temperature (T_c) assumed. However, a large difference occurred when considering the rotational speed (N_t) necessary to obtain a turbine efficiency (η_t) of 80 . Shaft speeds varied from 10,000 rpm for FC-82 (a 3M fluid) to 50,000 rpm for R-11. These turbine speeds were predicted based on a similarity technique described in detail by Balje (1962).

It is interesting to note that FC-82 can be operated as a direct drive turbine at 3600 rpm yielding a turbine efficiency of 70.. However, the heat exchangers and turbine are much larger resulting in a costly, bulky system. Therefore, it was concluded that these disadvantages do not justify the advantage of eliminating the speed reducer since efficient, inexpensive speed reduction is considered to be state-of-the-art technology.

The lower portion of Table I compares the performance of a number of air conditioning cycle fluids. The "ideal" compression horsepower is shown to vary only 6. for the fluids examined. However, a variation of 10:1 in required displacement is revealed. On this basis the field was limited to R-12 and R-22. R-22 requires a compressor with one-third less displacement than R-12, but the ideal horsepower for R-22 is slightly higher. Both R-12 and R-22 are considered acceptable. R-12 was selected for this solar demonstration project, and an R-12 compressor demonstrating the required efficiency was procured.

Based on the cycle assumptions of Table I the cooling coefficient of performance (COP, the ratio of cooling output to compressor input power) ranges from a value of 9 with an 85°F condenser to 4.25 with a 125°F condenser. Refrigeration cycle condensing temperatures around 125°F are appropriate for conventional, air-cooled systems, whereas the use of water cooling reduces attainable condensing temperatures to the range of 85 - 95°F with a corresponding augmentation in COP to 7 - 9. Since a cooling tower is required for the absorption air conditioning subsystems, a water-cooled condensing approach was selected for the RC subsystem to obtain the increased COP and allow a direct comparison between the two cooling approaches.

The effects of condensing and maximum cycle temperatures and regenerator efficiency on Rankine Cycle performance are shown in Figure 4. Over a practical range of values for this application, cycle efficiencies range from 7 - 14 .

Regenerator effects on system size and performance are revealed by Figure 5 for the RC temperatures shown. As the regenerator efficiency is increased, both system COP (the ratio of supplied cooling to RC heat input) and regenerator volume become greater. When regenerator efficiency exceeds 70 a large increase in heat exchanger core volume brings about only slight augmentation in system COP. However, since for reasonable overall heat transfer coefficients regenerator volume does not exceed 1/2 cubic foot until regenerator efficiency climbs above 90 , this value was selected as the design point.

Peak Rankine Cycle temperature is set principally by solar collector capacity, in this case to 200°F. For the ASHRAE specified ambient air temperature conditions (i.e., 90°F dry bulb, 75°F wet bulb) a conventional, off-the-shelf cooling tower can supply return water at 85°F, limiting Rankine Cycle condenser temperature to a value near 95°F. The remainder of the R-113 RC design state point conditions are shown in Figure 6 along with their corresponding enthalpies and densities. Turbine output shaft horsepower is 2.275 HP and cycle efficiency is 11.3%. Boiler and power condenser heat loads are 50,732 BTU/hr and 45,069 BTU/hr respectively.

Similarly, design state point values for the R-12 refrigeration cycle are shown in Figure 7. The resultant cooling COP is 6.971 and compressor input power is 2.028 HP. Evaporator and refrigeration condenser heat loads are 36,000 BTU/hr and 41,155 BTU/hr respectively.

A parametric study was undertaken to determine the effects on Rankine Cycle efficiency caused by deviations from the design point value for certain component performances and cycle conditions. The results, plotted in Figure 8, reveal that for the parameters studied, those having the most significant effect on efficiency are cycle conditions and turbine performance. Regenerator and pump efficiencies and system pressure losses have only secondary effects on the range 50 - 150 of design values.

Motor - Alternator

For most operating conditions turbine output power does not match the refrigeration cycle power demand. During those periods of time when solar-supplied Rankine Cycle output is above or below compressor demand a motor-alternator is provided. By using the alternator function when RC output exceeds AC demand, electrical power is supplied. When the AC demand exceeds the RC output, the electric motor makes up the deficit. Additionally, motor-alternator characteristics provide means for automatically controlling turbine speed.

The selected approach uses a standard squirrel cage induction motor tied to the 60 cps single phase line and physically coupled to the Rankine Cycle output shaft. The motor is energized whenever the air conditioning system is operating. The motor not only provides makeup compressor power during reduced solar input but operates as a generator feeding power back into the system when excess turbine power pushes the motor speed above synchronous. While the use of an induction motor in this fashion is atypical, it is estimated that generator efficiency will be comparable to motor efficiency which, for the type used here, is 72%.

Torque input and output characteristics are mirror images about the synchronous speed with full absorption or output occurring within 3 - 4% of the synchronous speed. The flat speed-torque characteristic of the induction motor provides another major system benefit in the control area. It ensures that the turbine, motor and compressor units remain at constant speed ($\pm$ 3%) regardless of changing load or input power level.

Off-design Operation

Figure 9 shows the effect of off-design condensing and solar heating water temperatures on Rankine Cycle power production. An increase in solar collector water temperature (85^{o}F), cause a 35% increase in power output by augmenting both R-113 flow rate and available turbine head. Similarly a reduction in cooling water temperature to 65^{o}F at the design point solar collector water temperature to (215^{o}F) also causes a 35 RC power increase. Figure 9 includes the turbine efficiency penalty of off-design operation.

Figure 10 shows how the amount of supplied cooling and the required compressor input power are affected by cooling water temperature. When the cooling water is warmer than design temperature the corresponding refrigeration condenser pressure and temperature rise. For that reason the liquid enthalpy value at the condenser outlet (and thus evaporator inlet) is higher leading to a net decrease in air conditioning. The corresponding required compressor input horsepower is of course increased due to the higher pressure ratio.

The curves of Figure 11 show percentages of cooling load carried by the solar-powered Rankine Cycle system for various off-design collector and condensing water temperatures. The amount of air conditioning supplied never exceeds the design point value of 36,000 BTU/hr because of the induction motor characteristics discussed previously. Whenever the RC condenser water temperature drops below 85°F and/or the solar collector water exceeds 215°F instead of providing more cooling the system generates electricity in addition to powering the compressor.

Test Results

The air conditioning unit was tested with compressor input power supplied by the motor in one case and the Rankine Cycle turbine in another. 'on with the motor alone provided 3.173 tons of air conditioning as 2.013 HP was supplied to the compressor. These figures show that the AC portion meets design goals. Rankine Cycle tests were underway at the time of this printing.

Estimated Manufacturing Costs

An analysis was made of the manufacturing cost of the system described here, although this system design emphasized performance, not cost. The cost of the heat exchangers and other purchased components are the OEM costs for 100 units. The turbine-gearbox, regenerator and pump costs were estimated by the author. The resultant manufacturing cost was $2500 - $3000.

This figure could be expected to be reduced in the future since costs are adversely affected for the RC vapor generator and the RC condensers because of the relatively high pressure (300 psia) design of standard refrigeration heat exchangers. Since the pressures for the RC loop are much lower (60 psia maximum) it would be possible to reduce system cost for high production quantities with low pressure heat exchanger designs.

Another factor weighing heavily on overall system cost is efficiency. Great increases in heat exchanger sizes are required to obtain small efficiency augmentations. For example, if only one RC condensing unit were used rather than the present two units, the amount of heat transfer area (and therefore the cost) of the RC condenser is cut by one half. However, condensing temperature is increased only four degrees. Therefore, the RC-AC system cost could be reduced; however, the entire collector-storage system must be included in the cost optimization in order to preclude an increased total system cost while decreasing RC costs.

Conclusions

1. Worldwide energy usage is increasing so rapidly that conventional fossil fuels may be unable to keep pace with the demand. The current unprecedented upswing in solar energy utilization is one factor contributing toward a solution to this problem.
2. The application of solar technology to the heating and cooling of buildings can reduce peak power electrical demands and prolong the availability of finite fossil fuel supplies.
3. The method most widely used to provide solar air conditioning employs the absorption refrigeration technique. Recent technological advances in the low-powered, organic Rankine Cycle area make it, too, worthy of consideration for solar cooling when combined with a conventional, vapor compression air conditioning unit.

TABLE 1

Comparison of Power Cycle Fluids

T_o = 190°F T_c = 90°F

Fluid	η_c	N_t, rpm	N_s	η_t
*R-113	.105	41,500	50	.80
R-114	.090	44,000	50	.80
R-11	.100	60,000	50	.80
R-142b	.087	57,000	50	.80
R-216	.094	28,300	50	.80
FC-82	.096	10,000	50	.80
FC-32	.085	3,600	18	.70

Comparison of Air Conditioning Fluids

T_{evap} = 40°F T_c = 100°F $T_{comp\ in}$ = 65°F

Fluid	Ideal HP/Ton	Displacement, cfm/ton
*R-12	.66	3.0
R-22	.68	2.0
R-11	.63	16.0
R-113	.63	37.8
R-114	.58	6.7

* Fluids selected for this application

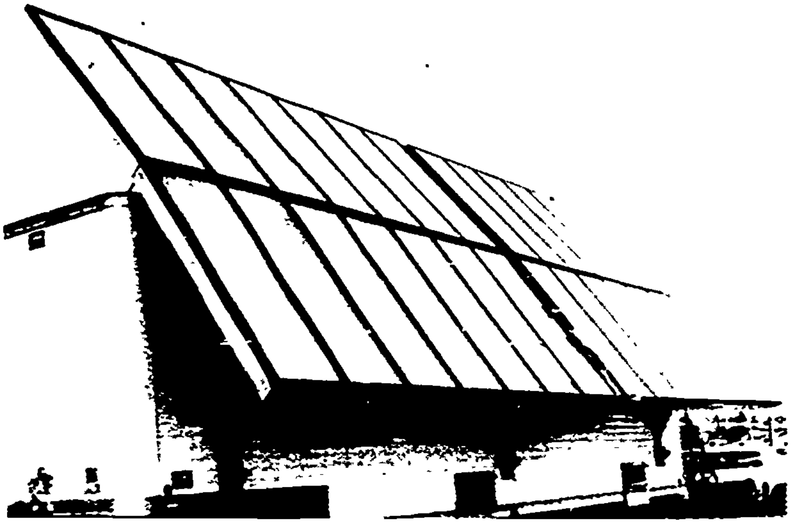


Fig. 1a. Honeywell's Mobile Solar Energy Research Laboratory.

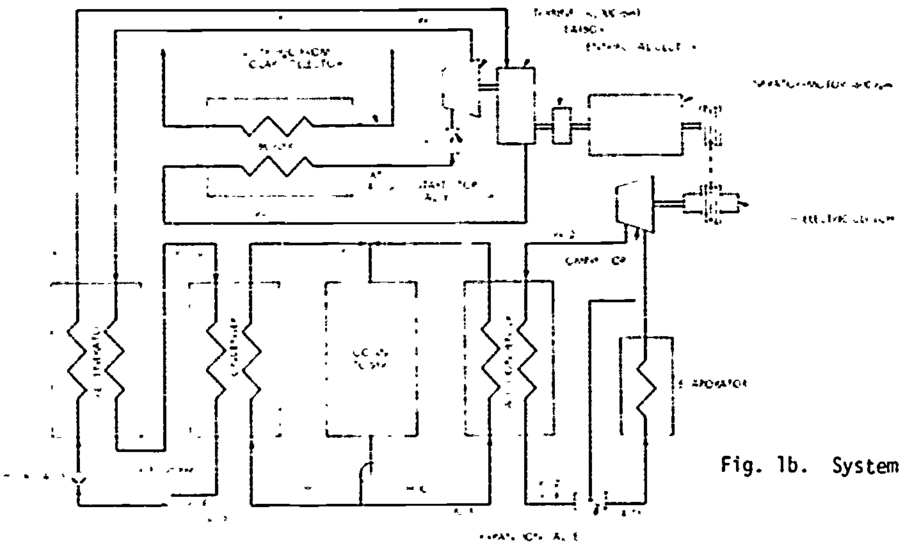


Fig. 1b. System Schematic.

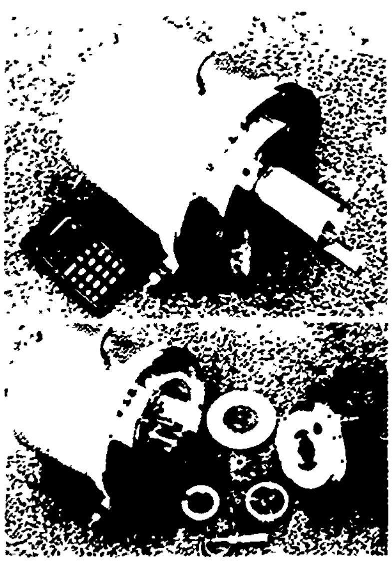


Fig. 2. Rankine Cycle Turbine -- Gearbox Unit Assembled and Disassembled

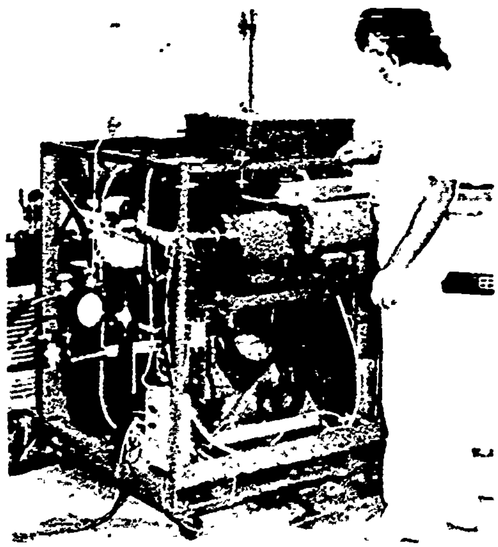


Fig. 3. Air Conditioning and Rankine Cycle Components on Test Stand

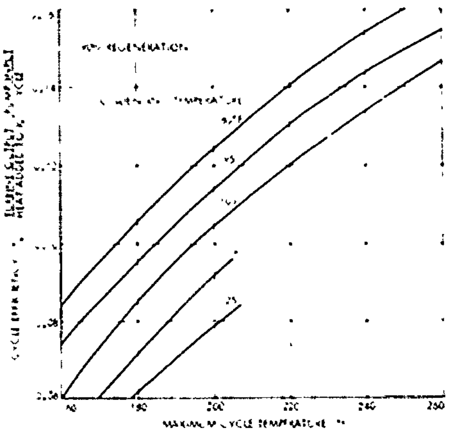


Fig. 4. Rankine Cycle Performance.

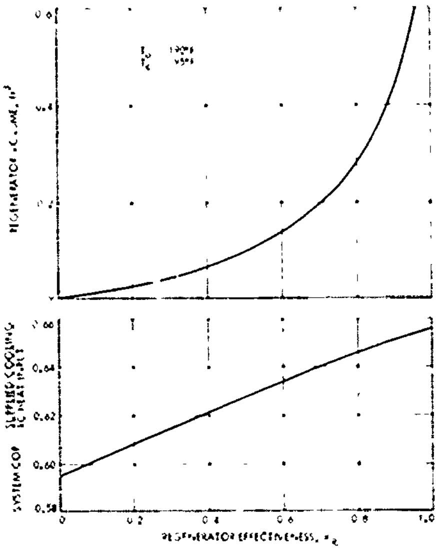


Fig. 5. Effect of Regenerator on System Size and Performance.

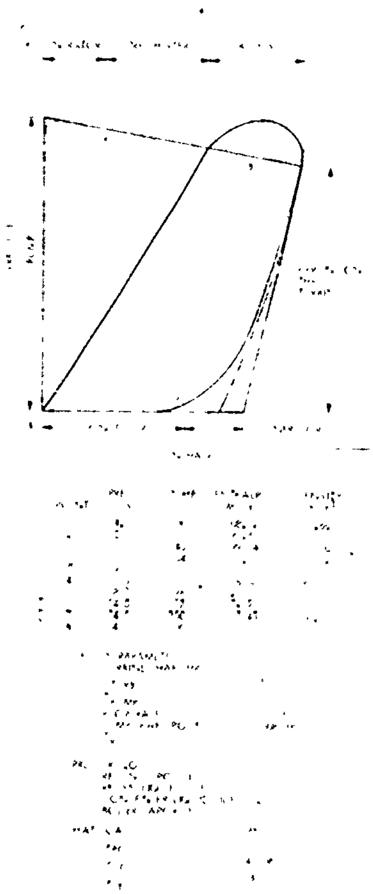


Fig. 6. R-113 Rankine Cycle Design Point.

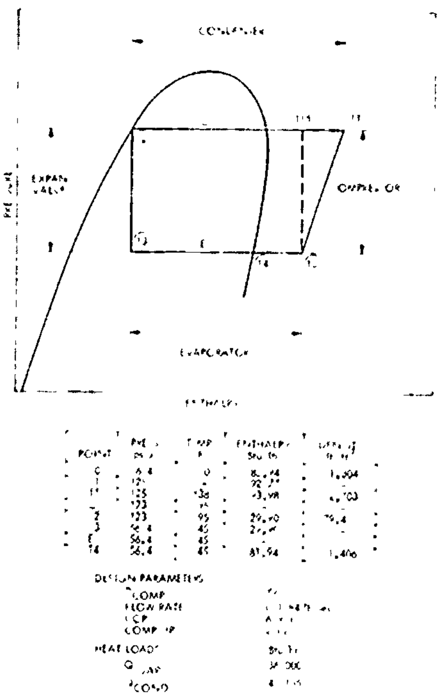


Fig. 7. R-12 Refrigeration Design Point.

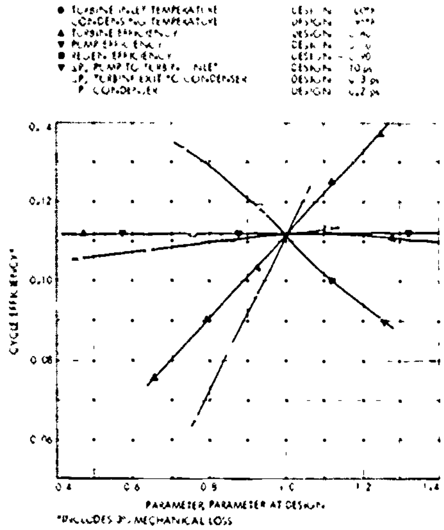


Fig. 8. Effect of Component Performance on Design Point Cycle Efficiency.

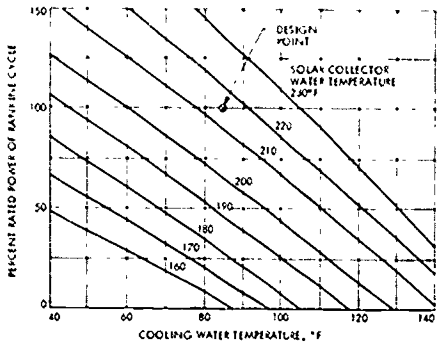


Fig. 9. Rankine Cycle Output Power vs. Water Temperature.

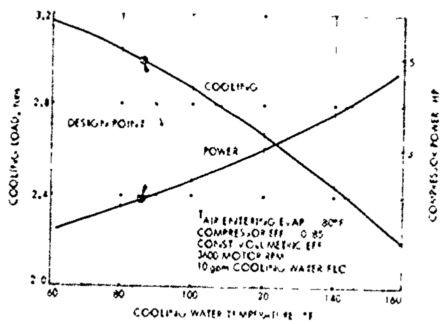


Fig. 10. Effect of Cooling Water Temperature on Air Conditioning Cooling Load and Compressor Power

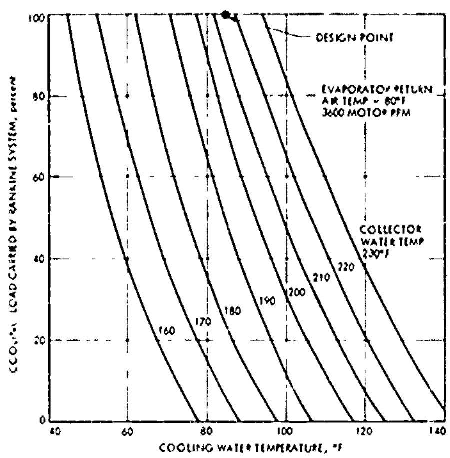


Fig. 11. Effect of Water Temperature on Rankine-Supplied Cooling.

Session V. Rankine Cycle

Commentator: Harry Buchberg

UCLA

Harry Buchberg, UCLA: I want to begin with a very short question for Curran. How long is your contract?

Curran: Approximately four months.

Buchberg: Thank you. I'd like to go to questions for Frank Biancardi, and I'm going to try to lump some of these questions together. There appear to be approximately three questions dealing with some aspect of efficiency. So let me run through all of these and if, Frank, you can handle the three of them all at the same time, it will save us a little time. First of all, what is the cycle efficiency penalty paid by virtue of using one fluid? F21 seems best for the power cycle, F114 for for the cooling cycle. Is your turbo compressor efficiency a polytropic efficiency? It seems low compared to units in production in centrifugal air and air conditioning systems. Does the 50 to 65% figure include both turbine and compressor compared to theoretical? What is your opinion to the statement of Curran on auxiliary energy, that is Rankine machinery efficiency must be better than .3 to the shaft, compare with conventional electrical sources?

Biancardi: Let me start with the last question and work backwards. Perhaps there was a tendency in the discussion by Curran to assume too high a performance not so much for the power generation part of it. There are transmission losses that weren't accounted for and there is a generator or motor efficiency that has to be accounted for and if you look at 30% over 31%, that says you're about 97% efficient and that's probably not true. I would say that he's a little on the high side in terms of what a Rankine cycle would have to do. Also that 31% is at design conditions and off design the 31 is probably going to be much lower. Now, in terms of the turbo compressor efficiency, I'm talking about the combined turbine and compressor efficiency. That's the product of the turbine and compressor efficiency in terms of what are its performance penalties with selecting one fluid. I don't believe they're very great. I haven't looked specifically at the numbers, but they might be on the order of 10%. The best fluid tends to be F113, F11 and F114 in the power cycle F21 is in there as well, but it's not clear at specific temperatures, which one is the best fluid? Did I miss any parts of the question?

Buchberg: No, I think you've handled just about all of it.

Curran: I wanted to emphasize that the choice of a 31% efficiency for the electric system is purely an example, and is not necessarily the number that should be used.

Buchberg: Thank you. I have another question here for you Frank. It says assuming that a working fluid temperature of 250 degrees can be attained, could United Aircraft or Hamilton Standard fabricate and deliver in 1974 a 50 to 100 ton turbo refrigeration unit, and if you can, the writer would like to know about cost, size, potential service reliability, etc., etc.?

Biancardi: I don't think there is any doubt that we could. I don't know if you would be able to pay the price or if he wants to start discussions, we'd certainly like to talk to him and consider the system.

Buchberg: Before you leave, would you like to comment on life expectancy between overhauls and operating speeds for a three ton unit with approximately 200 degree heat source?

Biancardi: Our design philosophy has been to have a ten year life. We could almost pick any number you like, would like to operate for 30 years, but not many things do, and we have considered the simplest design and no maintenance at all. The unit is initially so low in cost, you might say that you'd consider replacing it if you had any problems with another unit. I don't think we could specify any kind of meantime between overhaul or specification like that perhaps that question was prompted by some of the numbers that are talked about in terms of aircraft jet engines, and those very complicated units run as long as 3,000 hours before any kind of major overhaul, although they are inspected periodically and they are heavily instrumented. People know what's going on at all times.

Buchberg: The next questioner would like actually comments from Frank by you and by Burriss in regard to the gear box lubrication. Where the gear box is internal, how is it lubricated?

Biancardi: On the unit we're talking about there is no gear box. The turbine and the compressor are mechanically linked together and they run on the same speed. We have a number of installations specifically on the Lockheed L-1011, and the Boeing 747 where we do have power takeoffs. The machinery runs at speeds like 33,000 RPM and then there is a gear box at 3600 RPM which allows generation of several hundred kilowatts of power. So the concept of using a gear box is not something very foreign to a number of people in the field, but in the unit that I described, there would be no gear box.

Burriss: The turbocompressor design in our system doesn't use a gear box either. It has a single shaft with the turbine directly driving the compressor.

Buchberg: Here is another question for the same two speakers. What were speeds of turbo compressor systems? Where electric motors were coupled to the shaft, at what frequency did this work?

Burriss: The shaft speed for the unit that I showed in the presentation was 50,000 RPM. Any directly-driven alternator or motor would have to be a high-frequency high speed design. For example, at a 50,000 RPM shaft-speed, a 6 pole alternator will provide 2500 Hz output power. This would require some kind of solid state energy conversion device to be able to use this directly on the 60 cycle line, unless the output power is used internally in the system, to drive the cooling fans, for example.

Buchberg: Thank you. Biancardi, do you want to respond at all to that?

Biancardi: The test unit that I showed, ran at speeds of 26,000 RPM to an excess of 30,000 RPM depending upon the inlet temperature to the vapor generator. There have been a number of units in operation that have run at much higher speeds. Specifically the turbine that we used, was designed for much higher speeds than that, but we just used that as a convenient wheel in the demonstration system.

Buchberg: There are several questions concerning the high speed machines, in particular, one questioner asks whether there will be a noise problem. Burriss or Barber, would any of you care to respond?

Burriss: Machines of this type operating in a closed loop will run extremely quietly. The main noise will be the condenser and evaporator fans like most conventional air conditioning units.

Buchberg: Would you respond to the following? The question is, what type of automatic control refrigerant expansion device is used before the evaporator?

Burriss: In this case, it will be a conventional constant superheat type of control.

Buchberg: Then how do you insure that light load liquid will not get back to the compressor inlet and destroy it?

Burriss: Experience has shown that these compressors aren't sensitive to ingestion or carryover of small amounts of liquid. Originally, we did include a superheater in the inlet of the compressor but found it to be unnecessary and it has been deleted on subsequent vapor cycle systems.

Buchberg: Thank you. Question for Jerry Davis. Can you see any worthwhile payoff in using fossil fuel as a continuous topper to solar energy?

Davis: Yes, thermodynamically if you take a system where a very substantial portion of the heat input is by solar energy and then it's topped with a fossil fuel and you ask the question of what is the equivalent efficiency of the fossil fuel that you're burning in that cycle numbers can come out of 60 and 70 . So the answer to the question is it certainly cannot be disregarded. There was a previous question concerning the gear box and lubrication of the gear box. I believe that was our turbine system. We do have a step down gear reduction within the unit. It is oil lubricated, with an integral pump, and a very small amount of the lubricant continuously circulates with the working fluid. After some debugging, that system has operated quite satisfactorily.

Buchberg: A question for Robert Barber. Your solar concept is basically electric power generation, therefore, why not operate the cooling machine with purchased power at much lower cost?

Barber: Oh, that's a really good question. I guess Harold Hay suggested that there are other approaches. I think there are. From the points of view of initial cost, it is of course cheaper to run it electrically. I guess that we all know that. In solar energy of course, we would have lower operating cost, it's kind of an obvious question. Someone is trying to needle us, and I guess he knows the answer as well as I do.

Buchberg: I think you quoted the highest speed at 50,000 RPM machine of all of the suggestions today, and someone wonders about problems with this particular high speed machine in the way of life and maintenance and so on.

Barber: Well, it wasn't the highest speed. Jerry Davis showed the 70,000 RPM unit that they use in their vehicles. It's a 70,000 step down to 3,600. This particular unit is 56,000 stepping down to 3600, but there is a problem with life. I mean, the present unit doesn't have an indefinite life, it's designed for some 3,000 hours of operation on oil lubricated ball bearings but in production, the approach for longer life is to use hydrodynamic bearing. These units have successfully demonstrated in excess of 10,000 hours operation in air conditioning applications. This type of bearing is used on the DC8 air conditioning system where an 85,000 RPM turbo compressor operates on sleeve bearings with a 10,000 hour between overhaul record. So the technology is here.

Buchberg: Have you any experience with lubricant in the working fluid and for the refrigerant cycle?

Barber: Yes, the turbo gear box that we developed for the Thermoelectron unit was lubricated with a mixture of TFL and oil. In the unit we described here we have a high speed shaft seal, which is a limited leakage seal and the hermetic seal on the low speed shaft. Therefore, a small amount of the refrigerant oil in the gear box can leak into the system. Since the maximum cycle temperature is less than 250 degrees F. and it is quite common in a conventional air conditioning system to have 300 to 350 F compressor exit temperatures we're operating at less than conventional temperatures with the oil freon mixture.

Buchberg: I have one question here which is that the questioner would like to have a free-for-all between the advocates of absorption refrigeration, and the advocates of Rankine cycle refrigeration. But really at this point in time, there doesn't seem to be any useful purpose in this. The purpose of all of the programs that are now going on and going to be funded, are to shake out these questions and so, I don't really see any purpose in having such a free-for-all. Now there is another question. The questioner may have to elaborate on what he means. But he says, has any study been done on the possibility of using the screw type machines on a Rankine cycle system. I just don't happen to be too familiar with the screw type machines for that purpose, but I'll call on any of the speakers who would like to respond.

Barber: Yes, the rotary screw type compressors have been considered for use as expanders in this type of machinery. They do have the advantage that they couple well with the compressor, but the drawback is that leakage is difficult to control and their expansion ratio capability is such that multi stages are required to get the required efficiency. To my knowledge, they have not been successful although a number of people have attempted to develop rotary screw expanders.

Newton: I might point out one other thing. I think Robert Barber was speaking about dry screw type equipment. Most of it in the refrigeration field is lubricant flooded, and it does let you go to some higher ratios, but I think the big problem is that it does complicate the system and you must get into a pretty big system before you can afford that complication. I might point out perhaps that the automotive companies have tried to use screw compressors and found they took 30 or 35 horse power instead of 15 to drive the compressor.

Buchberg: Now, I think we can take just a couple of minutes or so with questions from the audience.

Anonymous question: The advantage of the two fluid system was reported to be that one could get electrical power off the same shaft in an alternate mode. Would it not be possible with a hermetically sealed unit to also get electrical power output from a rotating magnetic coupling or something that's on that shaft.

Burriss: Yes. An electrical generator can be driven by the turbocompressor to provide an electrical power output.

Barber: If I gave the impression that the two fluid system is the only one that is capable of auxiliary electric power generation, I certainly didn't mean to. Either system could be capable of auxiliary electric power generation. However, the generator speed could not be greater than 3600 PRM to produce 60 cycle power.

Beckman, University of Wisconsin: I'd like to propose the following problem. It seems to me that the systems that use electric energy for auxiliary power are in a sense doomed to failure if we have large scale application of the systems. For example, consider a modest amount of storage and three days of bad weather, everybody turns on their electrical, in effect, electrical air conditioning system. The power system has to supply the total load for all buildings in the area.

But I just don't think that electric utilities would really appreciate having to have this massive reserve power at all times.

Harry Tabor, Jerusalem: This is not really a question, it's just an excuse to get a word in edgewise. I didn't plan to come to this conference but I happened to be in the country and the program looked attractive. I've been disturbed by the very sharp sub division in the subject matter. Yesterday, we were told that we were allowed to talk about cooling, but not about heating. Today, in effect, we are told that we're allowed to talk about refrigeration, but not power generation from the sun.

We ought to get our picture absolutely clear. If we build a machine in which one end we put in sunshine, and the other end you get refrigeration, that's a solar refrigeration system. This might be said to be true of those systems where the expander and the compressor are all in the single unit, possible using a single fluid. However, if we have a diagram on the board, which shows a separate power unit with a pair of electrical wires coming out and driving an expander which would probably be electrically or mechanically driven, in my terminology this is not a solar refrigeration system. It's an exercise in solar power. And what we have to do to get our thinking clear is simply to determine how much we can afford to pay for a kilowatt hour of electricity or mechanical power produced from the sun and how much can we afford to pay if we compare it with, for example, a solar absorption machine?

I think if this sub division is made, the general thinking will be much clearer. One would get a much better picture of what can and cannot be done. A reference has been made to the fact that it looks as though we're getting near to the practicality of organic Rankine cycles. Such organic vapor machines are already on commercial sale. I'd like here to tell a story which some of you have heard. In 1958 to 1964, my colleagues and I were engaged in the development of an organic vapor engine designed in the horse power range to produce power from the sun for under-developed areas. We completed the work. It was demonstrated in a very crude form in the Rome conference in 1961 and a prototype was ready in 1964. We helped set up a production company - ORMAT - (I have no shares in the company!) and started making these turbines. They are low temperature turbines of very high reliability. They're sold all over the world. Not one of them is solar operated. The reason is very simple, that we should have learned earlier: the people for whom they were designed simple could not afford to buy solar equipment.

I'm sorry that this conference and this enthusiasm now for solar devices in the developed world hadn't taken place ten years ago, because we'd have been much better off today. The vapor turbine is a perfectly practical unit. I wouldn't like to say at what price it can be produced in large numbers because of course, up to date, they have been produced in very small numbers. I can only say, that many of the technological problems discussed here today have, in fact, been solved. The system is sealed, there is no lubrication and the manufacturers catalogue shows that in 1972, there were 300 of these units spread all around the world. They had accumulated over three million hours of operation and the MTBF (mean time between failures) was over 300,000 hours, i.e., it is a perfectly practical piece of machinery. Figure 1 shows a solar unit. In fact it's too good for the applications we have in mind here. Thank you.

Duchberg: One more question, and then I think we're going to turn the meeting back to the general session.

John DeSteese, Batelle Northwest: I have some comments that were pretty broadly based. I wonder, how many of the concepts we've seen described have enough thinking through the point of the concepts of being reliable long life equipment and would perhaps be invalid in terms of their eventual use. I'm talking specifically of the Rankine systems in which we must I think consider long life in terms of five, ten, 15 years of operation, and not the several thousand hours that is typical for machinery that is derived from aerospace technology. Similarly with a device that we saw last night, the Nitinol system, if we consider that no fatigue has been shown present for 10 to the 7 bending cycles, this is only 3,000 hours at 60 hertz. Can any of the proponents of the various system present information that would lead us to believe that their concepts are long life in terms of the several years that are necessary for commercial acceptance of these products when they are eventually developed?

Buchberg: Thank you. I'm awfully sorry, I know that there are additional questions and answers, but I'm going to have to turn the meeting over to our chairman Dr. Horowitz. Okay let's get an answer to that.

Biancardi: It may appear that I haven't been holding up my end of the questions, but I think that the comment that Dr. Tabor just made in many respects answer the previous question. He's talking about 300,000 hours. If he even operated 8000 hours a year, that's still more than 30 years type of operation and I think that that's plenty good. I don't think that anybody here is ready to say exactly how many hours and put up the kind of data you'd like to be completely sold. You buy a lot of equipment, do you ask your automobile dealer how many hours it's going to last? You certainly don't because you'd never buy an automobile if you did.

Jerry Davis: I was just going to say, there's absolutely no reason in the world why the kinds of machines that we're talking about can not approach and exceed the kinds of reliability that have been found in refrigeration and air conditioning systems today.

Francis de Winter (JPL): One area which had not been made clear in these proceedings concerns the thermodynamics of regeneration. Many other fluid choice criteria, such as sonic velocity, stability, pressure, freezing point, vapor density, latent heat, critical temperature, cost, toxicity, and such are quite straightforward. The benefits and drawbacks of regenerators (and fluids which require them) however seemed to merit an illustration. Because of this, a short discussion with some illustrative numerical results was prepared by the editor after the workshop, and inserted below.

In "wetting fluids," such as water or F-21, isentropic expansion through an expander brings the vapor closer to the saturation line. One can end up with wet vapor at the expander exit, even if one has used a significant degree of superheating. This situation is almost invariably obtained in Rankine cycles using water. One can run into significant erosion problems with high velocity wet steam. One advantage of "wetting fluids" is however that the exhaust vapor is close to the saturation temperature of the condenser. One does not have to dump high temperature heat, out of which more power could have been extracted.

In "drying fluids," such as F-114 and many other organic fluids, isentropic expansion through an expander takes vapor further away from the saturation line. One can not possibly end up with wet vapor which might erode turbine blades. The disadvantage is however that one is left with high grade heat at the expander exit, in the form of highly superheated vapor. If this is dumped directly into the condenser, one incurs a thermodynamic penalty. The usual way to minimize this penalty is to "recycle" this heat, by using the superheated vapor to preheat the pressurized boiler feed with a regenerator. The regenerator is of necessity relatively large; it is a gas-to-liquid heat exchanger, and gas heat transfer coefficients are generally small.

Some sample cycle calculations were made on F-21, a "wetting fluid," and F-114, a "drying fluid." F-21 and F-114 have virtually the same saturation pressure-temperature line. At 100^{0}F, the saturation temperature one might have in the condenser of a typical Rankine cycle used for air conditioning, the saturation pressure of F-21 is 40 Psia, with F-114 it is 46 Psia. At 250^{0}F, achievable with a good flat plate collector, the saturation pressure of F-21 is 292 Psia, with F-114 it is 300 Psia. The "wetting" and "drying" nature of the fluids can be seen in the relative slopes of the isentropic and saturation lines shown on the vapor side of the Pressure-Enthalpy plots prepared by E.I. Du Pont De Nemours & Co., reproduced in Figures 2 and 3 below.

The calculations involved a 100^{0}F condenser temperature, and for F-21 a boiler temperature of 250^{0}F with a boiler superheat of 20^{0}F (to 270^{0}F) to avoid wet vapor at the expander exit. A number of comparable F-114 cycles were calculated, both with and without regenerators, to compare cycle efficiencies. The overall efficiency of the boiler feed pump was taken to be 0.75, the overall efficiency of the expander was taken to be 0.75, and the effectiveness of the regenerators (see Kays and London, 1958) was taken to be 0.75, except in case 8, in which it was taken to be 1.00. These numbers are arbitrary but fairly reasonable.

Liquid (saturation) densities at 77^{0}F (taken from Du Pont Bulletin B-2) were used to calculate compression work. In the regenerator calculations, it was found that the vapor side was the side with the minimum heat capacity (Cmin), as per Kays and London (1958). For F-21, a superheat of 20^{0}F was used at 250^{0}F boiler temperature, for an expander inlet temperature of 270^{0}F. This was sufficiently superheated so that with 75 efficient expansion the expander exit vapor was dry. For the calculation of the expansion work in F-21, the isentropic lines were extrapolated into the wet saturation region as if no change of slope or behavior occurred at the saturation line. It should be noted that for an expander which operates totally in the dry region, peculiarities of the wet region are irrelevant. For the rest, the calculations followed standard thermodynamic textbook procedures. No pressure drops or heat losses were included.

The results of the calculations are shown in Table 1. Some comments on the results follow.

a) Without regeneration, "dry" F-114 is less efficient than "wet" F-21.

b) Regeneration brings F-114 closer to F-21, at the cost of having to include an extra exchanger. If the regenerator is effective enough the cycle efficiency of F-114 can perhaps become slightly better than F-21.

c) F-114 may have somewhat better high-temperature fluid stability than F-21, although at the temperatures in question this may not be important.

d) F-21 is somewhat better for Rankine cycles at these temperature levels than is F-114, since the critical point is at a somewhat higher temperature and heat addition in the boiler is hence at a more evenly high temperature.

e) Heat addition at a higher temperature produces penalties in solar systems, since it forces collection temperature up and collection efficiency down. The F-21 "advantage" discussed in d may hence not be as advantageous as one might think. Regeneration, by pushing the average collection temperature higher, also imposes penalties in this regard. If multistage expansion is used, this collector penalty may make it inadvisable to use "feedwater heaters" in a solar system.

f) From the table of results it can be seen that superheating without regeneration in F-114 does not increase the efficiency significantly. With regeneration, superheating does boost the efficiency. This is quite logical, since one is replacing low temperature heat with high temperature heat.

g) It should be noted that in a heat pump, a fluid which is a "wetting fluid" in a Rankine cycle becomes a "drying fluid" and vice versa. The thermodynamic advantages also are switched,* but there is no simple equivalent of a regenerator applicable to a single stage heat pump.

* F-114 is a good heat pump fluid, and at one time was to be used in the air conditioning cycle of the B-70.

Table 1. Rankine Cycle Efficiencies of a "Wetting Fluid:" F-21, and a "Drying Fluid:" F-114, Showing the Effects of Regenerator Usage.

Case	Fluid	$T_{cond.}$ sat	T_{boiler} sat	T_{boiler} superheat	Regenerator Used	Cycle Eff.
1	F-21	$100^{\circ}F$	$250^{\circ}F$	270	No	13.37
2	F-114	100	250	250	No	11.06
3	F-114	100	250	270	No	11.07
4	F-114	100	270	270	No	11.95
5	F-114	100	250	250	Yes-75%	12.35
6	F-114	100	250	270	Yes-75%	12.90
7	F-114	100	270	270	Yes-75%	13.31
8	F-114	100	270	270	Yes-100%	13.83

The efficiency of a Carnot cycle between $250^{\circ}F$ and $100^{\circ}F$ is 21.1 and between $270^{\circ}F$ and $100^{\circ}F$ it is 23.3 .

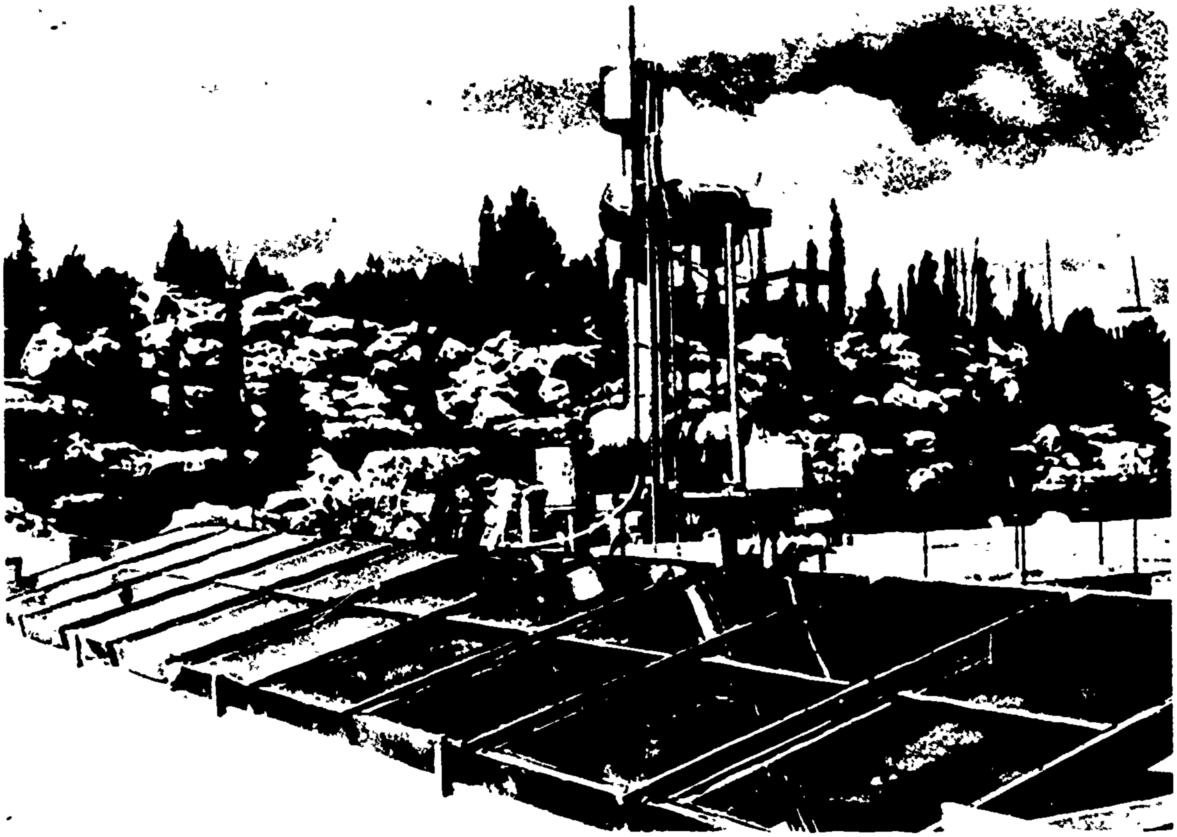


Fig. 1. Solar Energy Powered ORMAT Unit Operating in Israel.

PRESSURE - ENTHALPY DIAGRAM

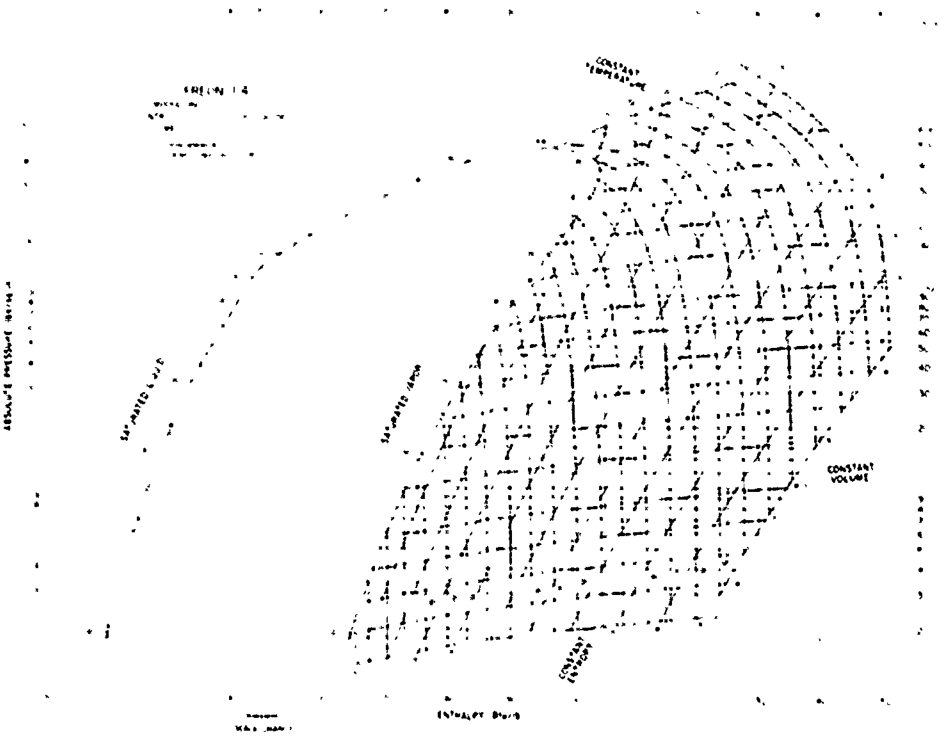


Fig. 2. DuPont Pressure-Enthalpy
Diagram for F-114, showing "drying" behavior.

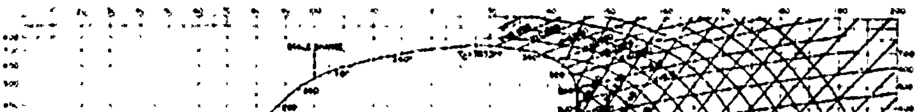


Fig. 3. DuPont Pressure-Enthalpy
Diagram for F-21, showing "wetting behavior.

Summary Session

WORKSHOP CLOSING REMARKS

Harold Horowitz

NSF

When we started this morning, I told you I was going to try very hard to finish this session at 11:30 and that gives me five minutes for whatever summary we could possibly hope to do for the workshop meeting that we've had. I talked with Redfield Allen yesterday. I don't know if he's in the audience at this time, or whether he's deserted us at this point, quite a few people have deserted us. They had earlier airplanes. Professor Allen was responsible for the equivalent to the effort that JPL made for this workshop in connection with the first workshop that was related to the heating and cooling of buildings with solar energy held last March in Washington. We were comparing notes on where we see ourselves today as against where we saw ourselves then. He shared the same kind of sense almost disbelief that we could have moved so far down the line in that short period of time. Less than a year. At that time, we saw cooling as our most difficult area. We still see cooling as our most difficult area but it's almost incredible to me still that nine months later we are able to put together a program with such a number of interesting and appropriate presentations with so much substance to them, and so many ideas that offer promise for future development. Certainly, in contrast with some of the speakers Wednesday evening, I think we have a lot of enthusiasm to go forward with at this point, rather than some sense of pessimism that was expressed Wednesday evening. The absorption people are enthusiastic, the desiccant people are enthusiastic, the solid state people are enthusiastic and the Rankine people are enthusiastic. I wonder when we'll meet our next solar cooling workshop? Will it be nine months? Six months? I don't know, but I'm sure that 12 months from now we will have a new set of presentations which will offer considerable progress over where we are today. It's a very hopeful sign. I think it's the note on which I would like to end this workshop and thank you all for coming and spending a very long day yesterday. If you were here for the ASHRAE meeting, this meant an extremely long week. It is a testimony to your interest in this subject and it's that kind of interest that will eventually solve the technical problems that are facing us in this area. Thank you very much.

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The following list includes not only the references mentioned by all of the authors, but also some other references of interest in the solar cooling field.

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