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RANKINE CYCLE MACHINES FOR SOLAR COOLING

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16. ABSTRACT

The Department of Energy of the United States of America has initiated a vigorous effort to develop and demonstrate practical uses of solar energy to heat and cool buildings, to process agricultural products, and to provide thermal and electrical energy for industry. One significant part of this effort is the research, development, and demonstration of Rankine cycle machines using fluids heated by solar energy rather than by coal, petroleum, natural gas, or nuclear fuels.

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I. INTRODUCTION

Some of the oldest archaeological sites in the world indicate solar energy was used passively to heat dwellings and to preserve food by dehydration. Wood or grass was probably the first form of stored solar energy actively used by man. It has only been during relatively recent times that the form of energy consumption has progressively changed from wood to coal to petroleum and natural gas. Since World War II, nuclear energy has been employed to provide electrical power for a world whose use of energy is rapidly approaching the time when conventional energy production may not be able to satisfy the demand. Many of the world's nations and communities have begun to seek alternative energy sources to sustain their economies or to help them improve the physical welfare of their people. Solar energy is being aggressively pursued by many nations, even by those whose fossil energy reserves were commonly considered to be ample until just the last 5 or 10 years. Many of the less developed areas of the world lack the stored energy reserves and the technological base upon which to build a society which can perhaps delay the foreseeable energy revolution. Indeed, most of those nations which are fortunate to have a highly developed technology, and some reserves of fossil fuels, are becoming increasingly concerned about the availability of energy in the decades ahead.

The Department of Energy of the United States of America has initiated a vigorous effort to develop and demonstrate practical uses of solar energy to heat and cool buildings, to process agricultural products, and to provide thermal and electrical energy for industry. One significant part of this effort is the research, development, and demonstration of Rankine cycle machines using fluids heated by solar energy rather than by coal, petroleum, natural gas, or nuclear fuels.

The Rankine cycle machine uses the principal of thermal expansion of a hot gas or of a hot fluid changing to gas at a lower pressure. During this process, work can be accomplished by suitable machinery — such as a turbine. Most of the world's electrical energy is now provided by turbines. They use fossil and nuclear fuels to heat water to a sufficiently high temperature so that an efficient thermal expansion to water vapor occurs across the multiple stages of the turbine. Shaft power is thereby produced, which is then used to turn electrical generators or other machinery.

The solar powered Rankine cycle machine differs primarily in the source of the energy used to heat the working fluid and in the fluid itself. The source is solar energy captured by appropriate collectors and transferred, not to water, but to a fluid which has a lower boiling point (e.g., a fluorocarbon refrigerant). It is this refrigerant which produces work across the turbine as it changes to a vapor at a lower pressure.

Recent developments in three such devices, being managed by the Marshall Space Flight Center (MSFC) for the Department of Energy (DOE), are briefly discussed later in this report.

II. DEVELOPMENT BACKGROUND

The Energy Research and Development Administration (ERDA) was the agency which evolved into DOE in October, 1977. The Solar Heating and Cooling Program of DOE includes both the development of systems and subsystems for heating and cooling of residential and commercial buildings as well as the demonstration of commercially available equipment installed in various types of buildings all across the United States. One objective of this Government program is to stimulate a viable solar heating and cooling industry. Requests for proposals from industrial and commercial interests were solicited in 1975 for various categories of solar systems and subsystems. It was recognized that some of this equipment was already suitable for the commercial market, but needed to be demonstrated nationally and that some of this equipment needed further development before it could be considered marketable. The three development efforts discussed were selected from among a group of proposals which represented the current state-of-the-art in this technology. The three Rankine cycle development contracts are with (a) AiResearch Manufacturing Company of California, Torrance, California; (b) General Electric Company, Philadelphia, Pennsylvania; (c) Honeywell, Inc., Minneapolis, Minnesota. Since the three design approaches differ significantly, it is appropriate that each of them be discussed separately in the next section. It should also be mentioned that development efforts are being pursued using the desiccant principal, but are of less maturity and will not be presented here.

III. RANKINE CYCLE DEVELOPMENT

A. AiResearch Manufacturing Company (NASA Contract NAS8-32091)

The heating and cooling systems, in development under this contract, employ a vapor-cycle heat pump using refrigerant R-11 as the working fluid. The heat pump features a motor driven centrifugal compressor whose speed is controlled such that its capacity equals the heat load. In the heating mode, solar thermal energy is captured by the collectors in the low temperature range of 5 to 27°C (40 to 80°F) and is processed to a higher level appropriate to heat the conditioned space. Seasonal Coefficients of Performance (COP) in the range of 8 are anticipated.

The vapor compression loop of the heat pump is reversed from the heating mode to the cooling mode. Solar thermal energy is used in a Rankine power loop to drive the heat pump compressor in the cooling mode of operation. The integral electric motor augments the Rankine engine when needed. The design temperature range of the solar heat source is from 68 to 104°C (155 to 220°F). The COP in the cooling mode is predicted to be approximately 0.7.

Three sizes of systems are being developed: 2.7, 22.7, and 68.2 metric tons capacity, (3, 25, and 75 U.S. tons).

A typical schematic of the solar heating and cooling system is shown in Figure 1. The turbine is inactive in the heating mode of operation. Hot water from the system's thermal energy storage tank is circulated through a tubular heat exchanger. The refrigerant R-11 is then evaporated in the tubes and the vapor is directed to the motor-driven centrifugal compressor. Since the motor is mounted on the same shaft as the compressor, they rotate at the same speed. To permit high speed operation of the motor, it is controlled by a solid-state converter. This converter receives its electrical power input from the 60 Hz main supply and converts it to high-frequency alternating current to power the motor.

The vapor from the compressor is condensed in a second heat exchanger, which serves as the heat source to the water heat transport loop of the building. Whenever the storage water temperature is high enough for the heating requirements of the building, it is used to provide direct heating and bypasses the heat pump. When the storage tank temperature is below 5°C (40°F), the heat pump is not used and heating is provided by an auxiliary boiler.

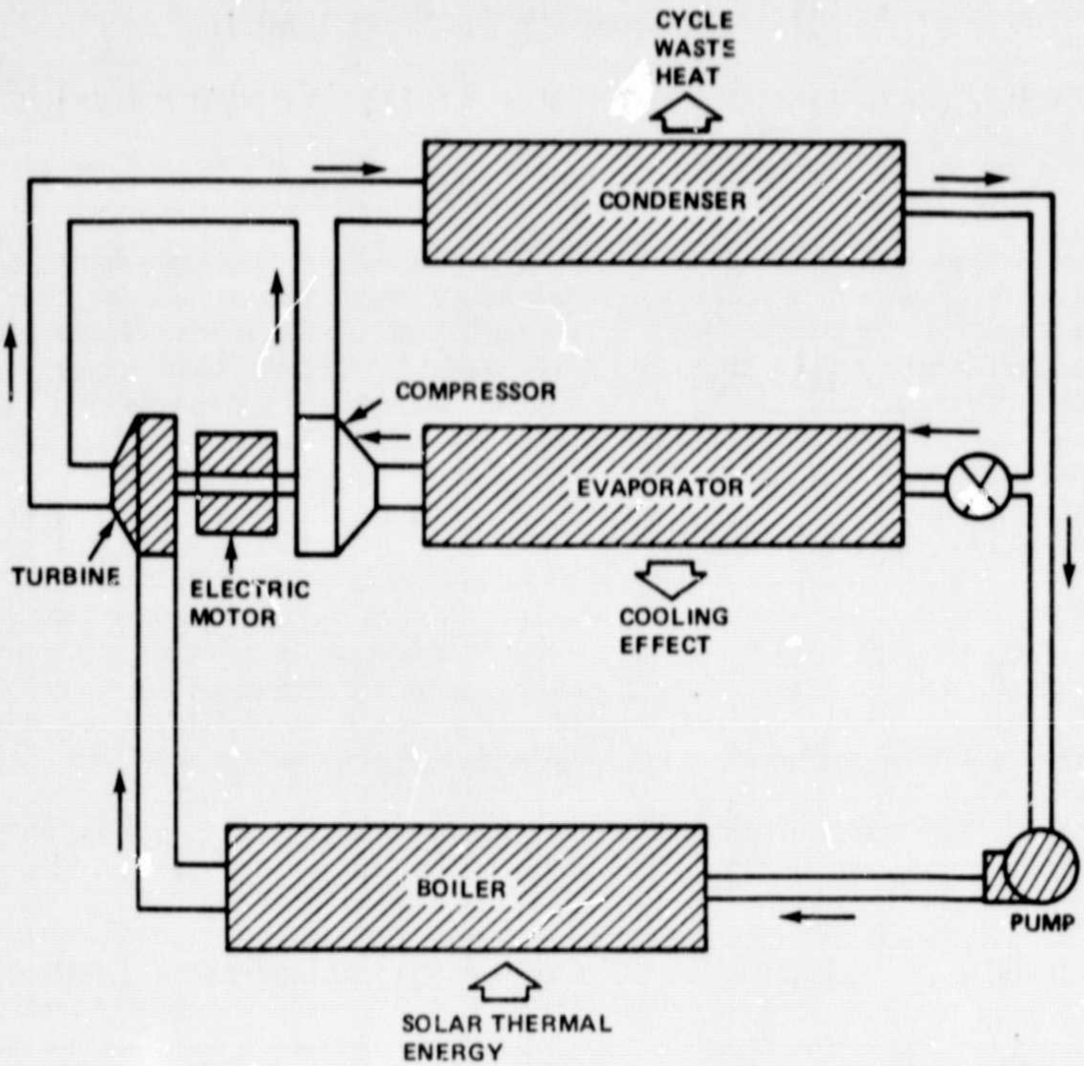

Figure 1. Rankine cycle heating and cooling subsystem developed by AiResearch.

The unique feature of the heat pump is the variable-speed motor. The system's controller commands the motor speed to a minimum value which will satisfy the heating requirements of the building. Compressor power requirements are minimized, and the maximum COP is obtained under all conditions.

In the cooling mode of operation, hot water from the storage tank is used to vaporize the refrigerant working fluid at a pressure of approximately 5.8 atm (85 psia). The vapor from the boiler is expanded in the turbine which drives the compressor in the refrigeration loop. To complete the Rankine power loop, the vapor from the turbine is condensed and the liquid refrigerant is pumped back to the boiler.

The 2.7 metric ton (3 U.S. ton) turbomachine and motor controller have been developed and the associated heat pump package is being tested to the standards of the American Refrigeration Institute. Four of these complete systems will be installed in single family residences in the second half of 1978 and will then undergo complete evaluation of performance and reliability.

The 22.7 metric ton (25 U.S. ton) turbomachine and motor controller are in their final stages of development. The 68.2 metric ton (75 U.S. ton) turbomachine and motor controller will be integrated with the heat pump subsystem in 1978 and installed for operational performance evaluation.

B. General Electric Company (NASA Contract NAS8-32092)

The Rankine cycle solar driven heating and cooling system being developed under this contract also uses a heat pump, but in a different configuration. Units with cooling capacities of 2.7 and 9 metric tons (3 and 10 U.S. tons) are being developed which can satisfy a significant portion of the residential and small commercial market requirements in the mid-1980's.

This system schematic is shown in Figure 2 and features the mating of a high performance vapor compressor of conventional design with a high efficiency vertically mounted expander in a hermetically sealed package. An electric motor within the sealed unit provides power to drive the compressor when sufficient solar energy is not available. The expander is a low-speed, two-stage, multivane rotary device which is connected to the compressor by an overrunning magnetic drive clutch assembly. The system uses a higher temperature than is available from conventional flat plate collectors. A unique vacuum tube collector provides a higher inlet temperature to the expander and allows the use of air side condensing. The system operates with two working fluids. The fluid in the Rankine drive loop is fluorocarbon FC88 and is highly stable up to temperatures of 260°C (500°F). It will give a large margin for improved performance and great stability.

The working fluid for the heat pump portion of the system is refrigerant R22, which allows the use of an extensive base of technology already available, and hardware requiring a minimum of development.

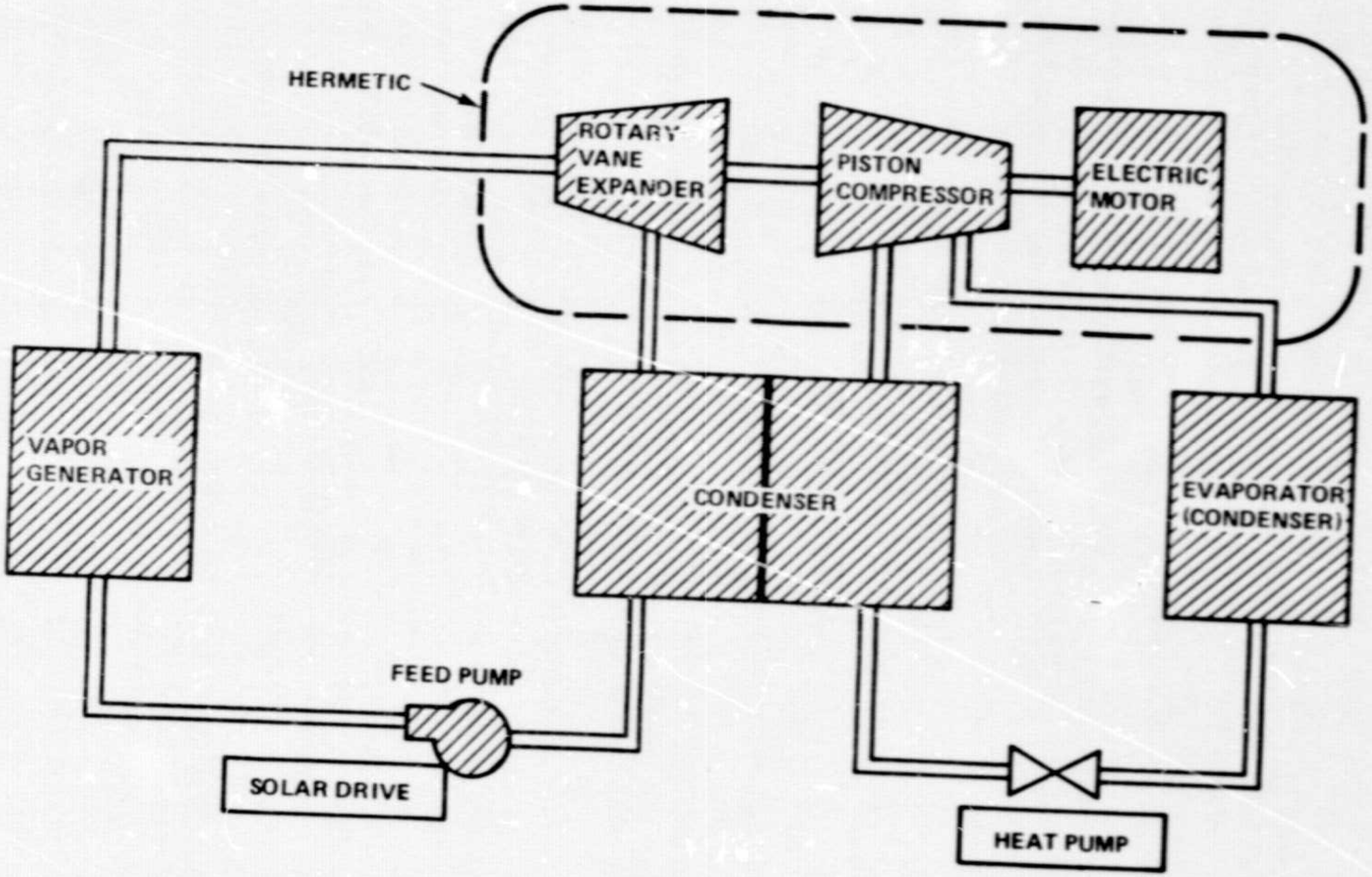

Figure 2. Rankine cycle heating and cooling subsystem developed by General Electric.

The status of this system development is that the Rankine drive expander is in the fabrication stage and will be tested soon. The designs of the heat pump components are completed and fabrication has started. A complete unit will be in operation later this summer. Prototype units will begin rigorous field testing in 1979.

C. Honeywell, Inc., (NASA Contract NAS8-32093)

This system is being developed as a family of heating and cooling units with capacities of 2.7, 22.7, 45.4, and 68.2 metric tons (2, 25, 50, and 75 U.S. tons). The generalized schematic for the system is shown in Figure 3. This is the only system discussed in this paper which is also being used to produce

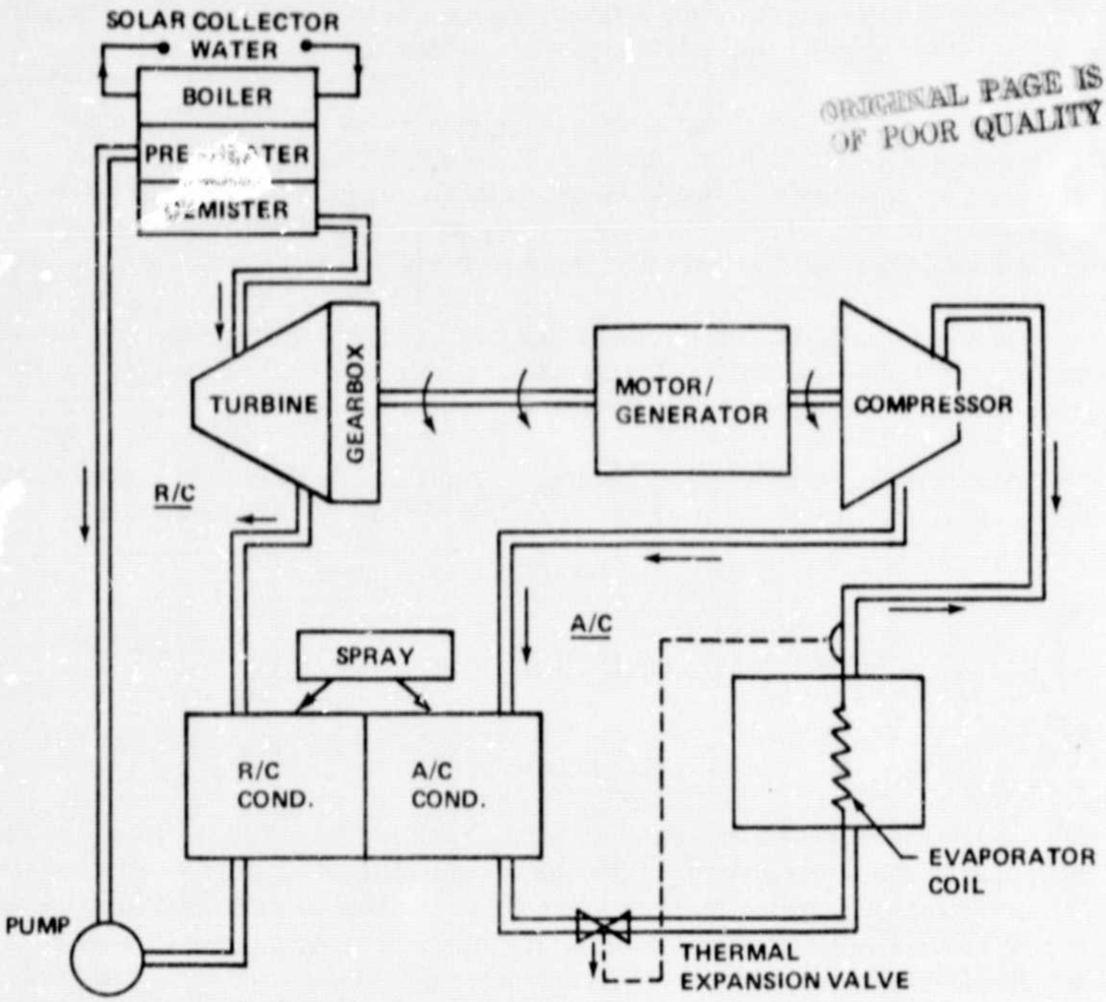

Figure 3. Rankine cycle heating and cooling subsystem developed by Honeywell.

electrical power. This is significant since there are many applications in many parts of the world which require electrical power whether or not there is a requirement for cooling. In fact, the Rankine cycle machine can be configured without a cooling compressor and will provide simple shaft power or electrical power if desired.

The central system is either in the heating mode or the cooling mode, as determined by manual switchover, which will be automated in later versions. Heating of the conditioned space is accomplished directly from the solar collector array, from the thermal storage tank at night or during periods of cloudy weather, or from an auxiliary boiler. The cooling is provided by a solar-powered Rankine engine/auxiliary electric motor driven water chiller.

The system consists of (1) a solar collector loop which interfaces with the thermal storage loop through a tube-and-shell heat exchanger, (2) a Rankine cycle boiler and engine, and (3) a motor generator and water chiller.

In February, 1978, operational tests were conducted on a complete 22.7 metric ton (25 U.S. ton) system of Rankine engine, motor generator, and water chiller. The tests covered the operational range from the solar input design point of 90.6°C (195°F) down to an imput temperature of 65.6°C (150°F). The data obtained from the tests are given in Table 1.

It should be noted from Table 1 that even at the lowest solar input temperature to the Rankine engine, the parasitic power required was only 14.2 kW versus the 21.1 kW required for the electric motor driven compressor alone.

The status of this system development is that one system is operational, a second is under construction, and the remainder are in various stages of design.

IV. ECONOMICS AND COMMUNITY DEVELOPMENT

A. Economics

Previous studies have shown that the dominant factor in the total system cost is that of the collector. The number of collectors of a given design required to drive a Rankine cycle or an absorption cycle cooling machine is a function of the COP of the machine. For example, if a specific system has a COP of 0.5, two hundred collectors might be required; whereas, if the COP were 1.0, only half that number would be required for the same effect. It appears that a COP of approximately 0.8 is appropriate, cost wise, for a solar cooling system.

TABLE 1. RANKINE ENGINE DATA

1. Rankine Engine Output Without the Compressor

Solar Input Temperature °C (°F)	Condensor Temperature °C (°F)	Power Produced (kW)	Horsepower Developed
90.6 (195)	29.4 (85)	12.8	20
87.8 (190)	29.4 (85)	11.9	19
78.9 (174)	29.4 (85)	8.7	12.5
73.3 (164)	29.4 (85)	5.9	8
67.8 (154)	29.4 (85)	3.5	5.3
65.6 (150)	29.4 (85)	2.4	4.5

2. Compressor Coefficient of Performance = 5.78

3. Engine: 21.1 kW for an Output of 22.5 Horsepower

4. Combined Rankine Engine/Compressor at Constant Output of 22.7 Metric Tons (25 U.S. Tons) and Condensor Temperature of 29.4°C (85°F).

Solar Input Temperature °C (°F)	Evaporator Temperature °C (°F)	Parasitic Power for Subsystem (kW)	Horsepower Required
90.6 (195)	12.6 (54.7)	3.42	3.6
79.4 (175)	12.8 (55.1)	8.7	11
65.6 (150)	12.9 (55.3)	14.2	16

At the present time, and for the next 2 to 5 years, it appears that it may be cheaper to use fossil or nuclear fuels to heat and cool our homes and buildings or to provide electrical power. These fuels are fixed in quantity, and their prices are increasing as their availability is decreasing. Direct use of solar energy is now economically practical for space heating and hot water heating in many parts of the world. In the near future, solar energy will become increasingly attractive as a practical means of obtaining electrical power.

Given sufficient economic stimulation to enter mass production of Rankine cycle systems, the industrial interests in many nations should be able to produce such equipment for about the same cost per kilogram of hardware weight as that of an automobile (i.e., \$1.50 to \$2.00/lb).

B. Community Development

So many areas of this world contain communities already considered to be developed and many more which will be developed in the future. Both types will require power which may not be available from sources now considered to be conventional.

Three steps toward the proper utilization of solar energy are (1) conservation of energy, (2) passive techniques, and (3) active techniques. Solar energy should be given primary consideration in the renovation of existing structures and in the design of new buildings and communities. The cheapest, and generally the most practical approach, is to use passive solar design techniques to increase the heat gain of the buildings during the cooler months, and to decrease the heat gain during the warmer months. Along with increased amounts of thermal insulation and passive techniques, active solar systems should then be considered. Heating of residential domestic hot water has been shown in the DOE's demonstration programs to be practical today in most regions of the United States. Space heating has also been shown to be feasible where the heating was by oil or electrical resistance units. Solar assisted cooling, at today's cost for equipment and for conventional power, has not been established as economically feasible.

Several existing communities and some now in the planning stage in the United States are already increasing their utilization of solar energy. A few are making firm plans to also incorporate Rankine cycle machinery for cooling and electrical power generation. At least one major electrical utility is planning a new community to be constructed near a new nuclear generating plant. This community will use not only passive techniques, but solar heating and cooling with the Rankine engine. In addition, wind and photovoltaic systems will be considered.

V. CONCLUSIONS

Solar energy preceded the age of mankind and is abundantly available to most of the peoples of the Earth. Solar hot water and heating systems are already becoming economically feasible now. The Rankine cycle engines are nearing the end of development, and several are already in operation. The results to date look encouraging and show promise economically, technical problems are being overcome, and future applications with coming mass production should enhance the marketability of these solar devices to the consumer. The Rankine engine is available to convert the Sun's energy into either cooling or electrical power, or both, to help meet the future energy demands of the world.

APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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