DOE/NASA TECHNICAL MEMORANDUM

DOE/NASA TM-82442

SOLAR COOLING SYSTEM PERFORMANCE, FRENCHMAN's REEF HOTEL ST. THOMAS, U. S. VIRGIN ISLANDS - FINAL REPORT

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For the U. S. Department of Energy

U.S. Department of Energy

Solar Energy

(NASA-TM-82442) SOLAR COOLING SYSTEM PERFORMANCE, FRENCHMAN'S REEF HOTEL, VIRGIN ISLANDS Final Report (NASA) 25 p HC A02/MF A01 CSCL 10A

N81-33611

Unclas
G3/44 27695

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. DOE/NASA TM-82442	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Solar Cooling System Performance, Frenchman's Reef Hotel St. Thomas, U. S. Virgin Islands - Final Report		5. REPORT DATE September 25, 1981
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Harry Harber		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO.
		13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, DC 20546		
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This report was prepared from material furnished by Sunmaster Corporation and Carrier Corporation under ContractsDEN-00005 and DEN8-000007.

16. ABSTRACT

This report is a part of the Solar Heating and Cooling Development Program funded by the Department of Energy and is one of a series of reports describing the operational and thermal performance of a variety of solar systems installed in Operational Test Sites.

The Solar Cooling System installed in the Frenchman's Reef Resort Hotel Test Site, St. Thomas, U. S. Virgin Islands, used 956 Sunmaster Corporation evacuated glass tube collector modules which provide an effective solar collector aperture of 13,384 square feet. The system consists of the collectors, two 2500 gallon tanks, pumps, an Andover Controls Corporation computerized controller, a large solar optimized Carrier Corporation industrial sized lithium bromide absorption chiller, and associated plumbing. Solar heated water is pumped through the system to the designed public areas such as lobby, lounges, restaurant and hallways. Auxiliary heat is provided by steam and a heat exchanger to supplement the solar heat.

17. KEY WORDS	18. DISTRIBUTION STATEMENT UC-59a Unclassified-Unlimited

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	19	NTIS

MSFC - Form 3292 (May 1969)

For sale by National Technical Information Service, Springfield, Virginia 22151

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The Frenchman's Reef Solar Cooling System Final Report documents the history, the description of the system, and the operational performanse of the Solar Cooling System installed in the Frenchman's Reef Holiday Inn Hotel, St. Thomas, U. S. Virgin Islands.

2. BACKGROUND

As part of the Solar Heating and Cooling Program funded by the Department of Energy (DOE), the George C. Marshall Space Flight Center (MSFC) was responsible for the management, design, development, installation, maintenance, and operation of the Frenchman's Reef Solar Cooling System. The Frenchman's Reef site was designated as an Operational Test Site within the Solar Heating and Cooling Development Program in September, 1979 by the Department of Energy. (See Figures 1 and 2.)

Contract DEN8-000005 was awarded to the Sunmaster Corporation, Corning, New York, for the design, development, installation, and checkout of the solar energy collection system; Contract DEN8-000007 was awarded to the Carrier Corporation, Syracuse, New York, for the design, development, and fabrication of the Solar Absorption Machine (SAM) 120 solar absorption chiller; and Contract DEN-000021 was awarded to Raffa Industries, LTD., Ft. Lauderdale, Florida, for the installation of the SAM 120 chiller. The initial contract was awarded and work started in January, 1979, and the SAM 120 chiller installation was completed in July, 1981.

3. SYSTEM DESCRIPTION

Site: The Frenchman's Reef Holiday Inn Hotel is located on the southeastern point of land at the entrance to the Charlotte Amalie Harbor, St. Thomas, U. S. Virgin Islands, at 18°20' North latitude and 64°57' West longitude. The hotel has three large wings designated "B wing", "C wing", and "D wing" and a smaller detached "A wing". The hotel contains over 350 guest rooms, and has the lobby, ballrooms, a restaurant, a lounge, and several shops on the third and fourth levels of "D wing". The hotel's mechanical plant, called the "Total Energy Room", is located below the parking lot and contains diesel electric generating equipment, desalinization units, absorption chillers, boilers, a sewage treatment system, cisterns for fresh and salt water, and associated equipment. The hotel is essentially self sufficient in that it generates its own electrical power, produces fresh potable water from sea water, and treats its own sewage. In other than normal conditions power is available from the island's utility, and fresh water is purchased and delivered in trucks.

The individual guest rooms are cooled by conventional type air conditioner units installed in each room. The public areas such as ballrooms, restaurant, the lounge, lobby, and shops are cooled by chilled water produced by the large absorption chillers. The chilled water is also used to cool hot water delivered by the desalinization units to cold water service temperatures. Salt water is pumped from the sea some 90 feet below to a cistern where it is subsequently used by the desalinization units to produce fresh potable water, and to serve as a heat rejection medium for the absorption chillers.

Solar Cooling System: The Frenchman's Reef Solar Cooling System consists of two subsystems: the Solar Collection Subsystem and the Chiller Subsystem. (See Figure 3.)

The Solar Collection Subsystem consists of the following:

956 Sunmaster DEC-8A solar collector modules.

2 2500 gallon tanks.

7 Pumps with associated piping and valves.

Andover Controls Sunlogger solar controller with associated wiring, sensors, relays, and printing terminal which provides control and data acquisition functions.

Each of the Sunmaster DEC-8A solar collector modules employs eight evacuated glass tube solar collectors and one Argonne National Laboratories designed compound parabolic cusp reflector mounted to a support structure. The reflector serves to concentrate the solar radiation onto the glass tube absorbers throughout the solar day, maximizing the solar energy collection. The tubes are connected to common supply and drain manifolds which are insulated to minimize heat loss. Each collector module has an effective collection area of approximately 14 square feet, and the total field has an aperture area of 13,384 square feet. Of the 956 total modules, 354 modules are installed on "D wing", 390 are on "C wing", and 212 are on "B wing". Collectors are mounted on each wing, in two arrays: an upper array and a lower array for a total of six arrays. Each of the six arrays is serviced by its own pump. Arrays are oriented to the south and inclined 17° from the horizontal.

Two 2500 gallon tanks serve as storage and "sump" tanks. Two tanks, one higher than the other, were required in order to provide the necessary capacity and to be compatible with the hotel's load-bearing structure. Heated solar water returning from the collector arrays empties into the upper tank. A pipe located 8 inches above the bottom of the upper tank transports water from the upper to lower tank. The lower tank serves as a "sump" or reservoir and supplies water to the 6 collector array pumps. The location of the exit to the transport pipe in the upper tank provides a minimum 8-inch deep pool of heated water in the upper tank. Two pipes entering the bottom of the upper tank serve to carry heated water to and from the SAM 120 absorption chiller and cooling subsystem. In the event of a power failure or shutdown of the solar subsystem, as at night, the water drains from the solar collector arrays back to and fills both upper and lower tanks. Both tanks are insulated to minimize heat loss during the drain back mode.

Six pumps are used to pump water from the lower 2500 gallon tank to the collectors. One pump is provided for each upper and lower array on each wing. A bypass line drain-back valve is provided for each pump. The drain-back valve is spring loaded open, and electrical power is required to close the valve. Therefore, if an electrical power failure occurs or is cut off, the drain-back valve opens and permits the water in the collectors to drain past the pumps to the storage tanks. One additional pump is provided on "B wing" in the solar water return line to assist the hot water over a structural wall and to the upper tank. All other collectors drain by gravity to the upper tank.

The solar subsystem operation is controlled by an Andover Control Sunlogger Solar Controller. A pyranometer and temperature, and pressure, and flow rate sensors are installed at selected locations throughout the solar subsystem. A minicomputer in the "Sunlogger" controller acquires data from the sensors, records and integrates the data, and makes programmed decisions. The decisions are implemented by command signals sent to relays and switches, which, in turn, actuates pumps and valves and causes the system to operate. The "Sunlogger" can be programmed and data can be acquired by a remote station through a telephone link and modems.

The Chiller Subsystem consists of two large absorption chillers, pumps, piping, valves, a heat exchanger, and controls. One chiller, designated Chiller #2, is a Carrier Corporation Model 16JB018 lithium bromide absorption chiller nominally rated at 174 tons, and is powered by 10 psi steam generated by waste heat boilers integrated with the diesel engines exhaust system.

The second chiller, designated Chiller #1, is a specially designed lithium bromide absorption chiller developed by the

Carrier Corporation to be used with the Frenchman's Reef solar system. Chiller #1, designated as model SAM 120 by the Carrier Corporation, is nominally rated at 120 tons capacity at the Frenchman's Reef site conditions and has a coefficient of performance (COP) of 0.7.

Series chilling is employed with the chilled water flowing from the pumps, through Chiller #2, through Chiller #1, and then to the load. Sea water is used to remove chiller rejected heat. Both chillers can be used at the same time, or separately. When both chillers are employed at the same time, sea water is divided to both machines because of limited sea water availability and pumping capacity.

Thermal energy is provided to Chiller #1, the SAM 120, by hot water. The water can be heated by the solar subsystem, by means of steam and a heat exchanger, or a combination of both steam and the solar subsystem. A three-way valve in the hot water lines actuated by the "Sunlogger" controller controls the flow of hot water to the SAM 120. When the three-way valve is open, hot water flows from the upper tank to the pump, through the heat exchanger, to the SAM 120, and back to the upper tank. When the three-way valve is closed the hot water circulates from pump to heat exchanger, to the SAM 120, and back to the pump, eliminating the solar subsystem from the circuit. A manually controlled bypass line in the circuit provides the capability for increasing or decreasing the amount of water that is circulated to and from the upper tank.

A proportional valve controls the steam supply to the heat exchanger, thereby controlling the amount of heat added to the hot water. Steam is supplied from boilers at 125 psi. The temperature of the hot water exiting the SAM 120 chiller is measured, and if the temperature drops below a "set" temperature, a pneumatic controller actuates the proportional steam valve to permit steam to flow to the heat exchanger. As steam is added, the incoming hot water is heated and the exiting water temperature rises until the "set" temperature is reached. Then the controller adjusts the steam flow to maintain the incoming water at sufficient temperature to maintain the "set" temperature in the exiting water. Thus, steam can supplement the heat provided by the Solar Subsystem to the water, or steam can be used as the sole source of heat whenever solar heat is not available such as at night.

Instrumentation: Instrumentation for the solar subsystem consists of a pyranometer and temperature sensors, pressure transducers, flowmeters, wattmeters, and liquid level sensors, installed at selected locations throughout the solar subsystem and integrated with the Andover Controls "Sunlogger" solar controller. Data are acquired from 48 analog inputs and 8 discrete inputs. The "Sunlogger" controller is programmed to analyze the acquired data and to issue commands which causes the subsystem to operate as specified. The "Sunlogger" is capable of recording instantaneous real-time data, and for converting that data into a daily time-phased history. Both the instaneous data and the daily history are available to a remote station by use of a telephone coupler and commercial telephone links.

There is no permanent instrumentation installed on the cooling subsystem. Data was acquired by using a special portable instrumentation system that utilized temperature sensors, pressure transducers, sonic flowmeters and a pyronometer connected with a recording minicomputer. Data from the cooling subsystem was acquired using the portable instrumentation system over a 6-day period after the SAM 120 was installed.

4. SYSTEM OPERATION

The operating sequence begins in the solar day morning with all solar subsystem water stored in the two 2500 gallon tanks. If the solar subsystem has been operating on the previous day, the stored water has been maintained at close to operating temperatures by the insulated tanks. At 7:45 a.m., and with the upper tank temperature less than 250°F, the "Sunlogger" controller "wakes up" the system by turning on pumps. The pumps fill the collector arrays at approximately 150 gallons per minute for 20 minutes. After filling, the pumps stop and the water is held in the collectors until the temperature reaches 200°F. At 200°F the pumps are started and the water is continuously circulated from collector arrays to upper tank, to lower tank, to pumps, and back to the collectors.

When the temperature of the solar heated water returning to the upper tank exceeds 215°F, and the lower tank temperature reaches 210°F, and system pressure is over 5 psi, the flow of hot water to the SAM 120 chiller is initiated by the "Sunlogger" controller opening the three-way valve in the hot water line to the chiller. The "Sunlogger" controller automatically closes the three-way valve and terminates flow from the upper tank when the temperature of the water in the upper tank fails to exceed the SAM 120 exit water temperature by 4°F.

The hot water flows from the upper tank to the pumps, to the heat exchanger, to the SAM 120 chiller, to the three-way valve, and back to the upper tank where a baffle separates hot water returning from the collectors from the water returning from the chiller. The temperature of the water exiting the chiller and returning to the upper tank will depend on the chiller load and the heat content and temperature of the solar heated water. If the exit water temperature drops below the selected "set" temperature, the steam valve controller will cause steam to flow to the heat exchanger to supplement the solar heat and maintain the exit water temperature at the "set" temperature.

In the afternoon when the insolation has diminished or during periods of inclement weather when the sun is obscured and the upper tank water temperature drops and fails to exceed the SAM 120 chiller exiting water temperature by 4°F, the "Sunlogger" will close the three-way valve and terminate the flow of solar heated water to the SAM 120 chiller. Steam then provides the necessary energy to heat the water sufficiently to operate the chiller. At 5 p.m. local time, the "Sunlogger" is programmed to shut the solar subsystem down. Electrical power to the pumps and the drain-back valves is cut off, the spring loaded drain-back valves open to permit by-passing the pumps, and the water in the collectors drain to the two 2500 gallon tanks.

Whenever the electrical power fails, or when an over temperature sensor in the collector array senses a temperature in excess of 300°F, the drain-back valves open and the water in the collector arrays drain back to the two 2500 gallon tanks. When power is restored, the "Sunlogger" controller will close the drain-back valves and actuate the pumps to pump water to the collectors provided that the temperature in the collector arrays has not exceeded 300°F. On a clear day the over temperature sensor will normally prevent operation until the next day if power is interrupted longer than 30 minutes.

5. PERFORMANCE CONSTRAINTS

After the installation of the solar subsystem in late 1979, both the solar subsystem and cooling subsystem experienced several malfunctions which interrupted operation. However, during those periods of operations between malfunctions the solar subsystem performed consistently and reliably. Data was obtained from the solar subsystem and although that data did indicate the quality of performance, the overall assessment of performance was inconclusive because no instrumentation was installed in the chiller subsystem. Installation of sensors in the chiller subsystem required shutting the system down and cutting holes in the piping for insertion of the sensors. The shutting down of the hotel's cooling system was considered to be excessively disruptive to the hotel's operation and would impose undue discomfort for the guests; and it was decided to postpone instrumenting the chiller subsystem until installation of the new SAM 120 chiller in July, 1981. Subsequently, the MSFC developed portable Checkout Test Module (CTM) with its "strap-on" transducers and snesors which did not require penetrating the subsystem's piping was used. The portable instrumentation system became available at the time of the installation of the SAM 120 chiller in July, 1981 and was used in conjunction with the Solar Collection Subsystem's "Sunlogger" controller to acquire overall solar colling system performance data. The amount of time available for acquiring the overall system data after installation of the SAM 120 was limited, but the quality of the data was considered to be adequate to develop a realistic analysis of the solar cooling system performance.

The pump initially installed circulating hot water from the solar subsystem to the chiller was capable of delivering 200 to 420 gallons per minute from the solar tanks to the chiller. Subsequently, that pump failed and a standby pump was brought into operation. The standby pump used a larger motor and was capable of pumping over 850 gallons per minute (gpm) through the chiller. By manually opening the bypass line in the system, the flow to and from the upper solar tank was reduced to approximately 550 gpm. Both the 550 gpm to and from the solar tank, and the 850 gpm through the chiller exceed design flow rates for the solar subsystem and the SAM 120 chiller and tend to degrade the performance of the overall system. The site intends to replace both pumps in the near future with pumps that produce the flow rates specified for the solar and cooling subsystems. While it is concluded that the excessive pumping rates do degrade the performance, no data is available at this time to determine the degree and extent of the performance degradation experienced.

In late 1980, several collector modules were found where the transparent plastic film surface had delaminated from the compound parabolic cusp reflectors. Analysis indicated that dark plastic sheeting used to protect the modules during installation created a "green house" effect, and the resultant heat was sufficient to degrade the adhesive between the clear plastic surface and the reflector and produce delaminiation. The Sunmaster Corporation developed a repair kit that consisted of new reflectors in sections which could be slipped into place over the existing reflectors and bolted into place. The replacement reflector kits fitted and conformed to the shape of the existing reflectors such that no degradation of collector performance has been detected. Installation of the replacement reflector kit was completed in July, 1981 prior to SAM 120 installation.

6. PERFORMANCE SUMMARY

The performance of the system was demonstrated at two levels of completion. Initially, only the solar collection subsystem was monitored for performance when the operating interface was with an existing absorption chiller. Subsequently, the total system was monitored briefly after the existing chiller was replaced by the new SAM 120.

On March 19 and 20, 1980, tests were run on the Solar Cooling System with the then existing Carrier Corporation chiller model 16JB018 operating with solar heated water. The auxiliary steam heat was shut off and the chiller operated on solar heated water from 11 a.m. through 4:30 p.m. The following data acquired by the "Sunlogger" controller are compared with design predictions:

	Predicted	Actual
Insolation in Plane of Collector	1817 BTU/Ft^2 Day	1805 BTU/Ft^{2}Day*
Total Insolation Available		24.8 million BTU
Energy Collected	11.4 million BTU	8.7 million BTU*
Energy Delivered to Chiller	10.5 million BTU	7.8 million BTU
Energy Delivered vs. Collected Energy	92%	89.6%
Collector Efficiency (Energy Available vs. Energy Collected)		35%
Solar Subsystem Efficiency (Energy Available vs. Energy Delivered to Chiller)		31.4%

*Part of the day was cloudy. Approximate clear day insolation is 1925 BTU/Ft^2 Day and energy collected was 9.5 million BTU.

No chiller performance was acquired as there was no instrumentation installed on the cooling subsystem at the time of the test.

The second series of tests were conducted on the solar and chiller subsystems during August 3 through 9, 1981, after installation of the Carrier SAM 120 chiller. In addition to off-design hot water flow rates discussed earlier, climatic conditions were considerably less desirable than for the March, 1980 tests due to sporadic showers and periods of cloudiness interrupting the solar day. The following performance was shown for 12:59 p.m. on August 8, 1981:

Insolation	275 BTU/Ft^2 hour
Temperature of Water to Collectors	205.8°F
Temperature of Water Returning from Collectors	221°F
Flow Rate of Water Through Collectors	141 GPM
Energy Collected	1.07 Million BTU
Temperature Water Entering Heat Exchanger	207.2°F
Temperature Water Leaving Heat Exchanger	210.8°F
Temperature Water Leaving Chiller	205.3°F
Flow Rate of Water Through Heat Exchanger and Chiller	857 GPM
Heat Added by Steam in Heat Exchanger	1.54 Million BTU
Heat Provided by Solar	.81 Million BTU
Total Heat to Chiller	2.35 Million BTU
Temperature of Chill Water into Chiller	63.5°F
Temperature of Chill Water Leaving Chiller	59.1°F
Flow Rate Chilled Water Through Chiller	675 GPM
Cooling Load (Energy removed from Chill Water by Chiller	1.49 Million BTU
Chiller Coefficient of Performance (COP) (Cooling Load vs. Heat added to Chiller)	.63

Solar Collector Efficiency (Energy Available vs. Energy Collected)	28.9%
Solar Subsystem Efficiency (Energy Available vs. Energy Delivered to Chiller)	21.9%
Energy Contributed by Steam to Chiller	65.5%
Energy Contributed by Solar to Chiller	34.5%

Solar energy and steam heat add to make up the total energy required by the chiller for any set of cooling load conditions. The August, 1981 data shows that 34.5 percent of the energy to the chiller was contributed by the Solar Subsystem, but only 21.9 percent of the total energy available was delivered to the chiller. The March, 1980 test indicated that 31.4 percent of available solar energy was delivered to the chiller. Therefore, it can be expected that with better climatic conditions and with a hot water pump whose capacity matches the system design flow specifications of 450 GPM, the solar subsystem will deliver more of the available solar energy to the chiller. It is reasonable to expect that with a properly sized hot water pump and a 300 BTU/Ft^2 hour day, collector efficiencies could reach 35 percent, 31 percent of available energy would be delivered to the chiller, and that solar would contribute up to 48 percent of the chiller energy requirements for a 124 ton load. It is also reasonable to expect the chiller coefficient of performance (COP) to reach 0.7 with the proper pump.

7. REMARKS

The Solar Cooling System at the Frenchman's Reef Resort Hotel Operational Test Site is one of the larger solar projects in the development program. The size of the project and its location have made it uniquely valuable as a Development project. The experience derived from the project has contributed to program objectives to demonstrate solar energy as a viable alternate energy source for the nation.

It is unfortunate that the solar cooling system was not configured with the "design" flow rates and control "set points" when performance measurements of the total system were made. Additional measurements of the total system performance while operating to "design" specifications may be necessary at some later date to fulfill follow-on program objectives.

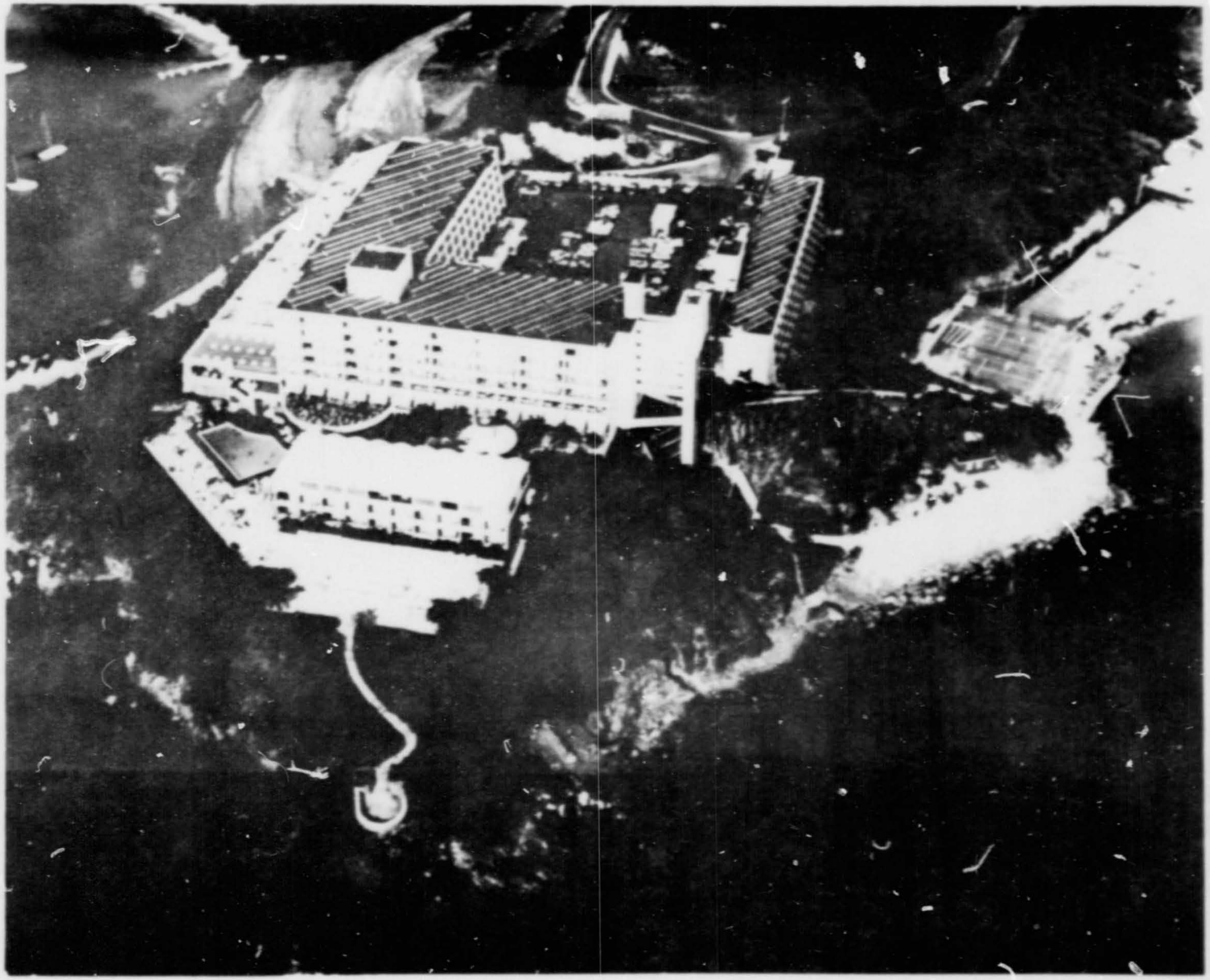
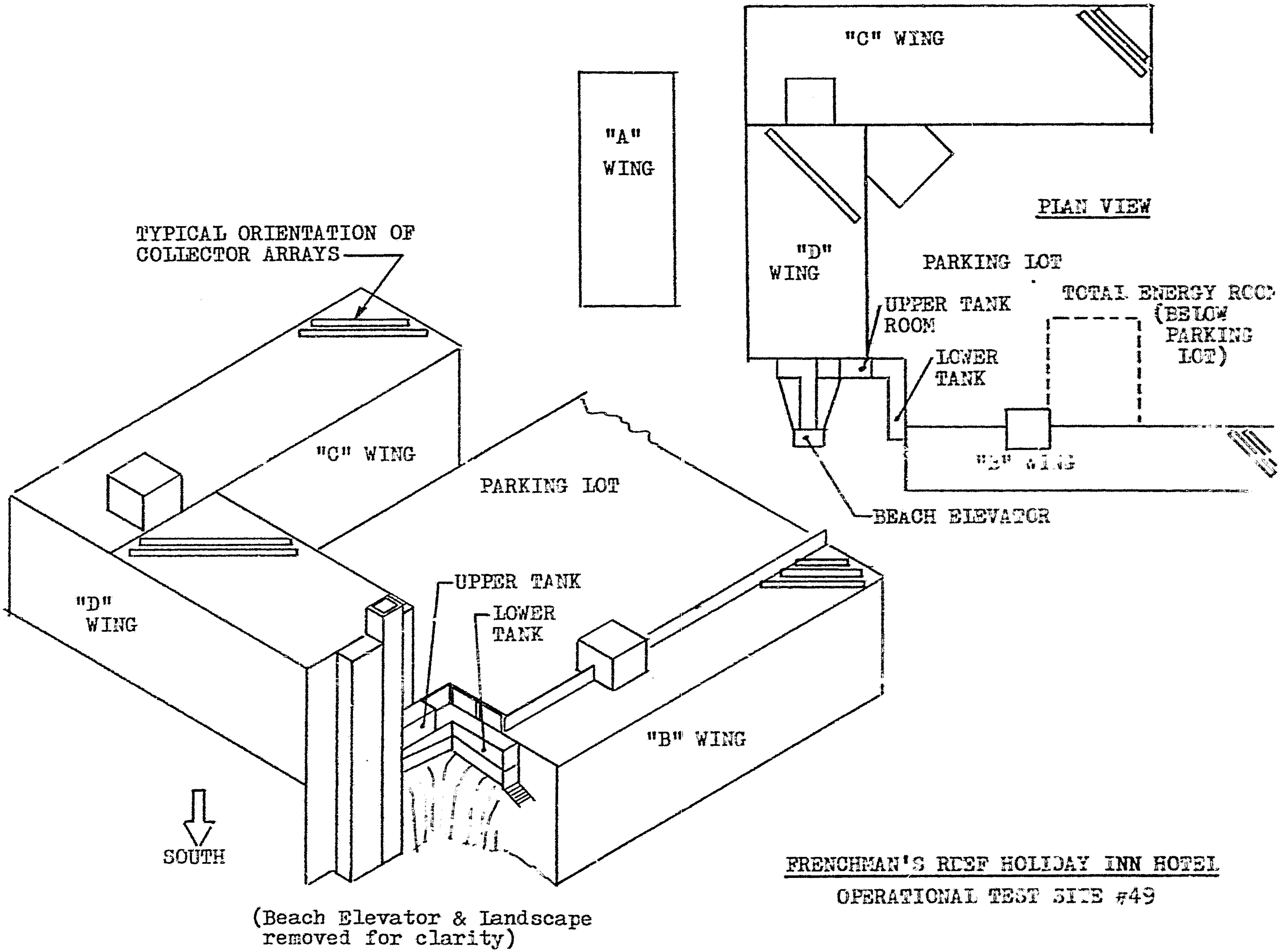
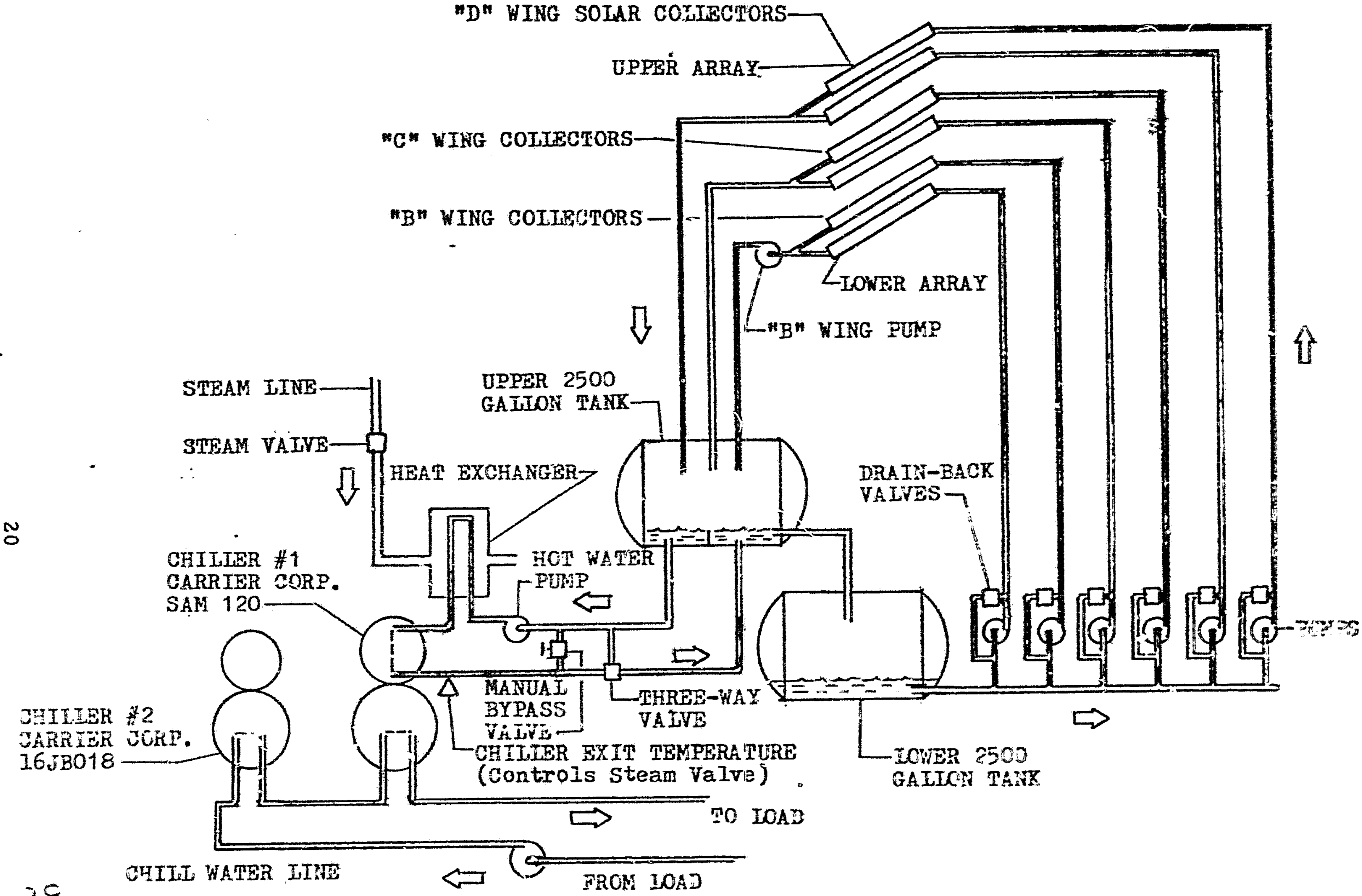


Figure 1: Frenchman's Reef Holiday Inn Hotel. Solar Cooling Operational Test Site



FRENCHMAN'S REEF HOLIDAY INN HOTEL
OPERATIONAL TEST SITE #49

FIGURE 2



FRENCHMAN'S REEF SOLAR COOLING SYSTEM

APPROVAL

SOLAR COOLING SYSTEM PERFORMANCE, FRENCHMAN'S REEF HOTEL ST. THOMAS, U. S. VIRGIN ISLANDS - FINAL REPORT

By Harry Harber

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.

William A. Brooksbank, Jr.

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Manager, Solar Energy Applications Projects