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Solar Cooling Techniques for Rural Areas: A Detail Review

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Abstract
There is necessity of cooling in rural areas of developing as well as developed countries having a large proportion of people living there, and in these locations, grid electricity is presently unavailable or not reliable, and availability of fuels are also difficult or too expensive. In order to obtain storage of vaccines and lifesaving drugs, food preservation and grain storage, refrigeration systems based on usage of solar energy can be considered to be the optimal solution for such areas which receive high solar insolation. The solar refrigeration can be expected to play a significant role in meeting the needs of people in the rural areas of developing countries for refrigeration. The improvements required are mainly in the areas of increasing system performance and lowering costs. With probable increase in the costs of conventional energy sources, it is expected that solar technologies will become competitive with the conventional system in future.

Keywords: *Photovoltaic, absorption, adsorption, rural*

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INTRODUCTION

Research into solar powered refrigeration systems has been active since the late 1970s. However, such systems have not been commercialized due to their high capital cost. For vaccine storage, a high capital cost may be acceptable; however in food preservation or comfort air conditioning, the capital costs must be reduced dramatically in order for such systems to become viable. Since conventional, electrically powered vapour compression refrigeration system may not be of much use in such areas, for essential application such as food and drugs preservations, alternative refrigeration systems are required. These are mainly: photovoltaic powered vapour compression system, continuous and intermittent liquid or solid absorption system and adsorption system.

A solar refrigeration system that could produce 250 kg of ice per day was installed in Tashkent, USSR in 1953. This system used a parabolic mirror of 10 m^2 area for concentrating the solar radiation. Solar adsorption refrigeration system with ammoniacates, sodium thiocyanates, activated charcoal, zeolite as adsorbents and ammonia, alcohols or fluorocarbons as refrigerants have also been in use since 1950s. Photovoltaic array directly coupled to an electric motor may become a simple and reliable system, suitable for use in remote areas, was mentioned by Blas *et al.* [1] The values of current, voltage, motor speed and electromagnetic torque at the operating point vary continuously as a function of the prevailing environmental conditions and the characteristics and configuration of the components integrating the system.

Atmaca *et al*. [2] simulated a solar-powered, single stage; absorption cooling system, using a water-lithium bromide solution. A modular computer program has been developed for the absorption system to simulate various cycle configurations and solar energy parameters for Antalya, Turkey. Chen *et al.* developed a new type of absorption refrigeration cycle that is co-driven both by solar energy and electricity, [3]. The principle of a heat transformer was applied to the absorption refrigeration system to increase its efficiency, a thermodynamic model describing the performance of the new cycle was developed and a computer program was written to evaluate its performance. The COP, condenser heat load, the theoretical minimum evaporating temperature and refrigeration capacity for a typical daily load of the system were calculated and compared with those of traditional absorption refrigeration systems. The results show that the new cycle not only overcomes some shortcomings of the traditional absorption cycle with unsteady energy input from a variable source such as solar energy, but also increases the system's coefficient of performance. Yaxiu *et al*. had done experimental research on a new solar pump-free lithium bromide absorption refrigeration system with a second generator [4]. By using the second generator, together with a lunate thermosiphon elevation tube, the required minimum driving temperature of the heat source was only 68°C compared to above 100°C, in traditional absorption refrigeration systems. Pilatowsky *et al*. study reports the applicability and the theoretical thermodynamic simulation of a solar driven monomethylamine-water single-stage absorption refrigeration cycle for milk cooling purposes in the rural regions of Mexico [5].

Luo *et al*. developed a novel solar-powered adsorption cooling system for low-temperature grain storage, which consists of a solar-powered water heating system, a silica gel-water adsorption chiller, a cooling tower and a fan coil unit [6]. The adsorption chiller is composed of two identical adsorption units, each of them containing an adsorber, a condenser, and an evaporator/receiver. Li *et al*. developed a no valve, flat plate solar ice maker [7]. There are no valves and measure gauges installed on this advanced device, also no moving parts are there on this device, activated carbon and methanol are used as working pairs for this no valve solar ice maker. Experimental results under both, indoor and outdoor showed that each subsystem, such as adsorbent bed, condenser, evaporator, demonstrated a good performance on system running processes; this no valve solar ice maker prototype is approached for practical application of mass production from the view of cost and techniques.

PHOTOVOLTAIC REFRIGERATION SYSTEM

Photovoltaic refrigerators operate on the same principle as normal compression refrigerators but incorporate low voltage (12 or 24 V) dc compressors and motors, rather than mains voltage ac types. A photovoltaic refrigerator has higher levels of insulation around the storage compartments to maximize energy efficiency, a battery bank for electricity storage, a battery charge regulator and a controller which converts the power from the battery to a form required by the compressor motor. A typical refrigerator layout is shown below (Figure 1). Most refrigerators include a freezer compartment for ice pack freezing.

Chungpaibulpatana *et al*. designed a photovoltaic/thermal hybrid solar system which is a combination of photovoltaic (PV) and solar thermal components/systems which produces both electricity and heat from one integrated component or system [7].

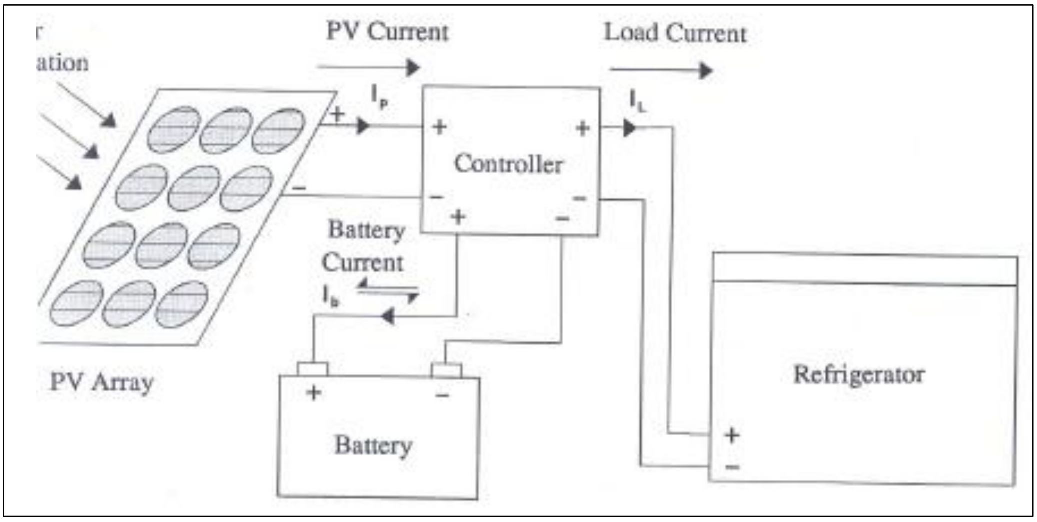


Fig. 1: *Typical Solar Photovoltaic Refrigerator Layout [8].*

Modi *et al*. describes the fabrication, experimentation and simulation stages of converting a 165 l domestic electric refrigerator to a solar powered one [9]. For the study, an old domestic refrigerator (165 l capacity) with the condenser tubes at the back and the compressor placed at the bottom is used. A conventional domestic refrigerator was chosen for this purpose and was redesigned by adding battery bank, inverter and transformer, and powered by solar photovoltaic (SPV) panels as shown in Figure 2. Various performance tests were carried out to study the performance of the system. The coefficient of performance (COP) was observed to decrease with time from morning to afternoon and a maximum COP of 2.102 observed at 7AM. Simulations regarding economic feasibility of the system for the climatic conditions of Jaipur city (India) were also carried out using energy project software called RET Screen 4. It was observed that the system can only be economically viable with carbon trading option taken into account, and an initial subsidy or a reduction in the component costs, mainly SPV panels and battery ban.

Kaplaris *et al*. reduced a convectional refrigerator to a SPV one; they reduced the cooling load and consequently the power required as shown in Figure 3 [10]. They increased the refrigerator insulation of polyurethane by 25 mm; as a consequence, the increase of insulation had reduction of the internal volume by 30%. Replacement of the door's double glass by insulation is to reduce the heat losses.

This change had as a disadvantage, the lack of the internal view to the refrigerator. A three phase brushless motor with permanent magnet was used in the compressor. This compressor is a DC one with variable speed running from 2000 to 3500 rpm. Due to this change, no DC/AC inverter was required.

Energy consumption fell down to 1.53 kWh/day, for refrigerating purposes with a 15 h operation of the compressor, while for conservation, the load was 1.7 kWh, with the system operating for 24 h. The alteration from an AC motor to a DC eliminates the requirement of inverter.

Hence, less power loss and better economics were obtained as a result. The use of a variable speed motor of the compressor increased the power transfer or solar insolation utilizability to the level of 92% for a speed value ratio 2.5.

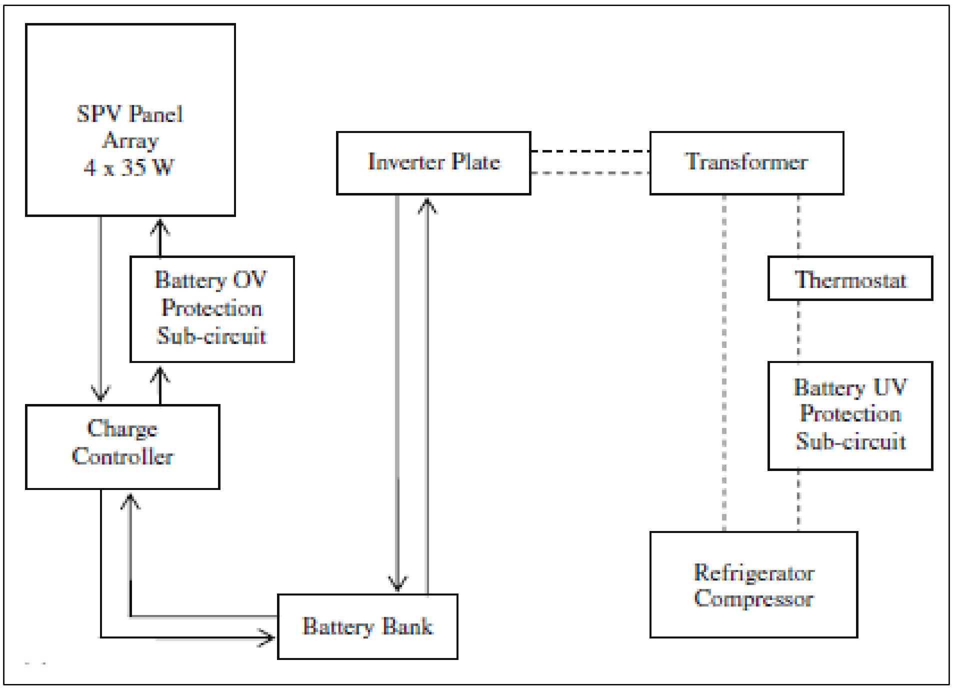


Fig. 2: *Block Diagram of the SPV System. The Dark and the Dashed Lines show DC and AC Flow [9].*

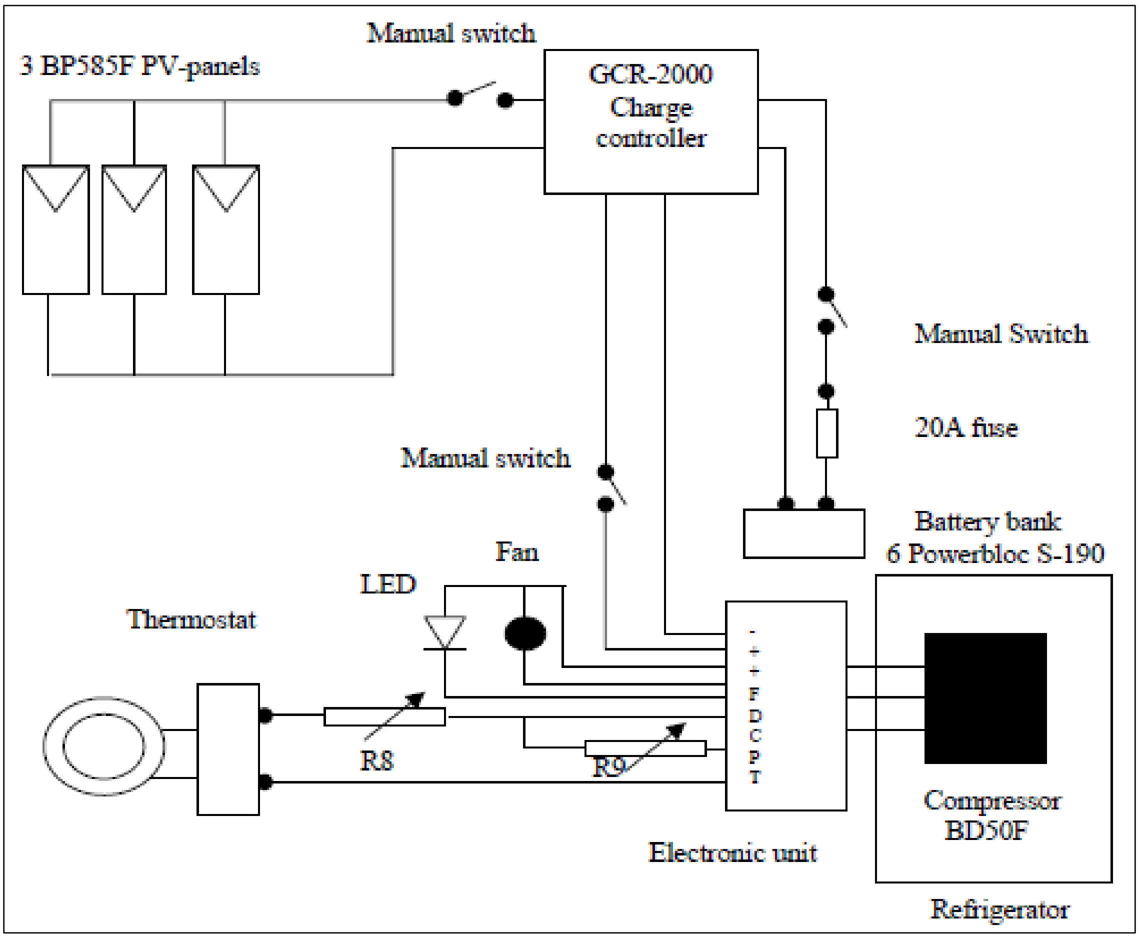


Fig. 3: *Modified Conventional Refrigerator [10].*

One should take care that at such a mode, there is a delicate element to be added, i.e. the thermostat to control the compressor operation. At a speed of 3500 rpm, the thermostat stopped for a time period when the compressor's temperature passed a preset level.

Ewert *et al.* developed and tested a photovoltaic system without the requirement of battery and inverter at New Mexico State University [11]. The photovoltaic direct drive solar refrigerator uses thermal storage, and a direct connection is made between the vapor compression cooling system and the PV panel. This is accomplished by integrating a phase change material into a well-insulated refrigerator cabinet and by developing a microprocessor-based control system that allows direct connection of a PV panel to a variable speed DC compressor, as shown in Figure 4. This allows for peak power point tracking and eliminates the need of batteries. This refrigerator stores thermal energy in a phase change material rather than storing electrical energy in a battery. For the phase change material, a nontoxic, low cost, water based solution was selected which has good freezing properties. The battery free solar refrigerator stores thermal energy in a phase change material.

A chest type cabinet with 110 mm insulation was used. For the phase change material, a non-toxic, low cost water based solution was selected which has good freezing properties.

Fig. 4: *Battery Free Solar Refrigerator [11].*

The Amount of phase change material was chosen in such a way so as to provide 7 days of cold reserve at a temperature of 29.5°C. For higher thermal efficiency, a good contact between thermal storage material and evaporator was made.

Cherif *et al*. presented the performances, the simulation responses and the dynamic behavior of a photovoltaic (PV) refrigeration plant using latent storage [12]. They substituted the battery storage with thermal, eutectic, latent or a hydraulic storage.

The measurements and the evaluation of these less battery storage systems at several climatic conditions and under load disturbances were studied to evaluate the PV system reliability and to compare its performances with classic battery storage systems. The LBSS refrigeration plant is shown in Figure 5.

It consists of mainly three parts:

- An electronic unit: comprising of the PV panel and the dc/dc and dc/ac converters;
- A thermal section: which contains the refrigerator and the cooling sections; and
- A control/data acquisition chain: for the PV system control and management.

Yaxiu *et al.* performed experiments on a new solar pump-free lithium bromide absorption refrigeration system with a second generator [4]. By using the second generator, together with a lunate thermo siphon elevation tube, the required minimum driving temperature of the heat source is only 68°C, compared to above 100°C, in traditional absorption refrigeration systems.

Based on the horizontal-tube falling-film method, the performance of the absorber can be enhanced by the second generator, due to an increase in the differential concentration of the solution between the inlet and the outlet of the absorber and an increase in the temperature difference between the inlet and the outlet of the cooling water in the absorber as shown in Figure 6.

This leads to an improvement of the performance of the overall refrigeration system. The maximum coefficient of performance (COP) approaches 0.787.

The apparatus consists of a simulated solar-heat collector, a lunate thermo siphon elevation tube, a gas-liquid separator, a second generator, a condenser, a falling-film absorber, a falling-film evaporator, a solution reservoir and a heat exchanger.

Pilatowsky *et al*. studied the applicability and the theoretical thermodynamic simulation of a solar driven monomethylamine-water single-stage absorption refrigeration cycle for milk cooling purposes in the rural regions of Mexico in Figure 7 [5]. The use of the solution heat exchanger and the milk precooler improves the thermodynamic efficiency and reduces the solar heating load fraction.

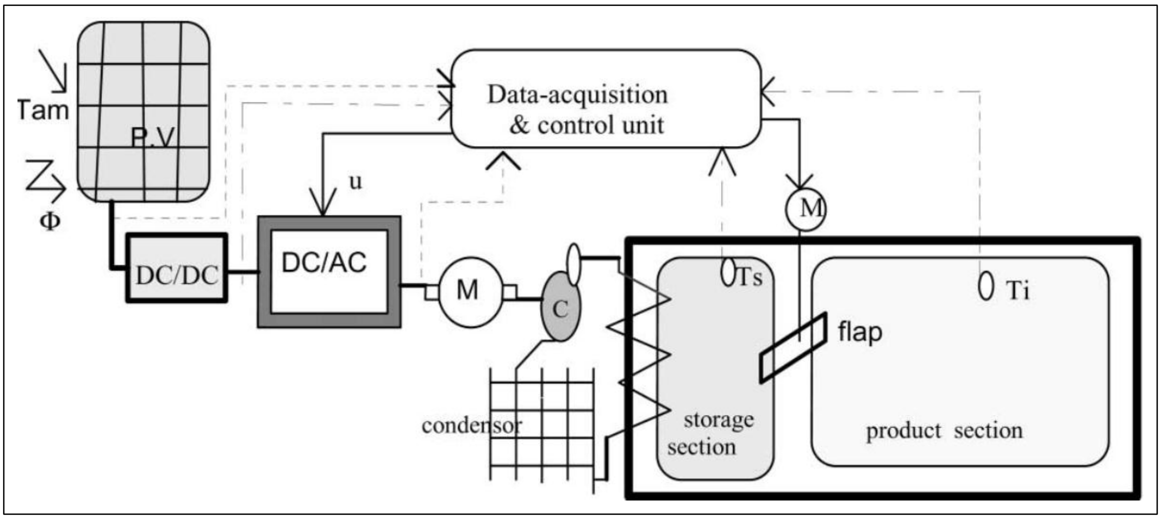
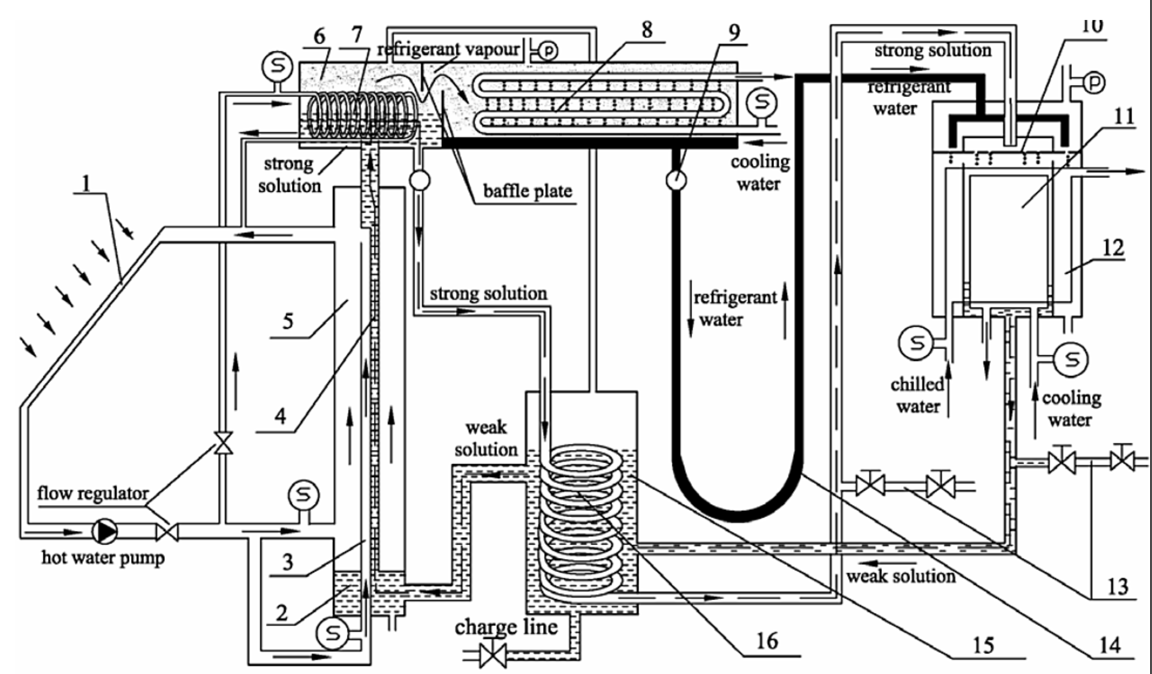


Fig. 5: *Description of the PV LBSS Refrigeration Plant [12].*



1. Simulated solar-heat collector; 2. Elevation tube; 3. Inner tube 4. Lunate channel; 5. Straight channel outside outer tube; 6. Gas–liquid separator; 7. Second generator; 8. Condenser; 9. Liquid-flow meter; 10. Drip pan; 11. Absorber; 12. Evaporator; 13. Solution-sampling device; 14. U-shaped throttle tube; 15. Solution reservoir; 16. Heat exchanger.

Fig. 6: *Pump Free Absorption System [4].*

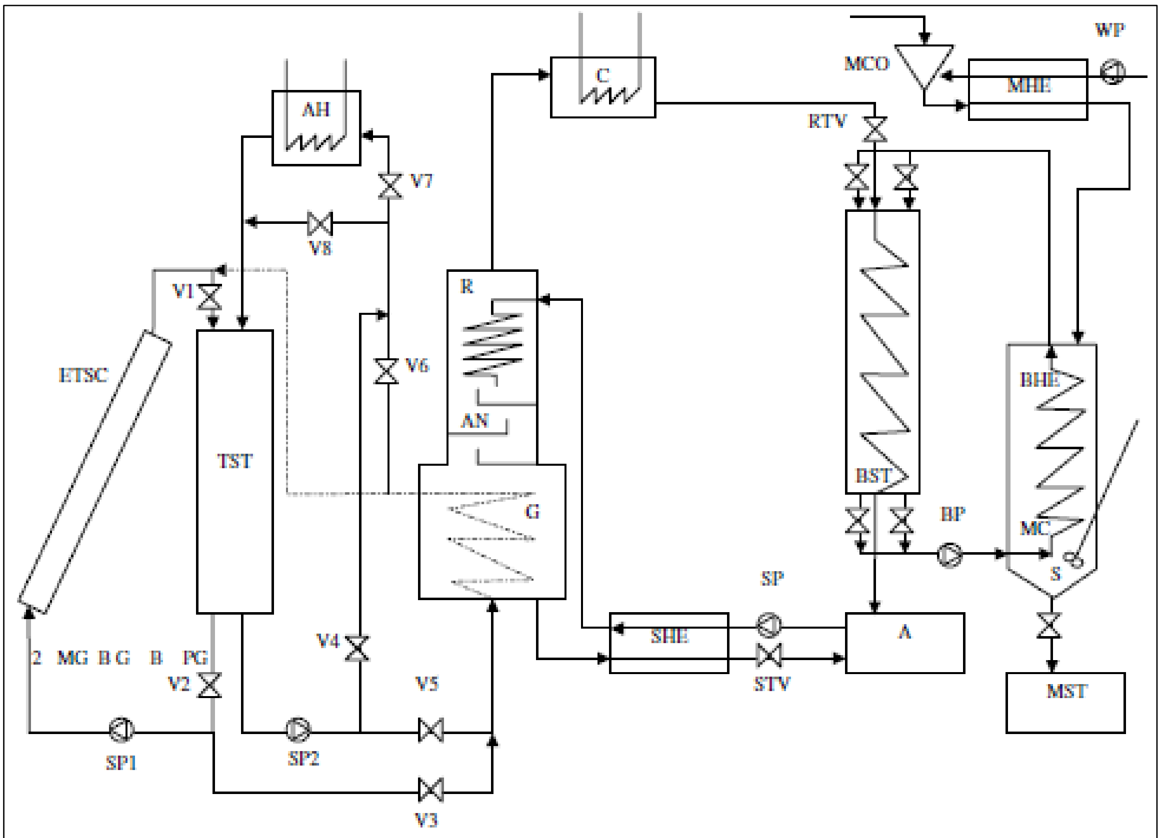


Fig. 7: *Schematic Description of the Monomethylamine-Water Absorption Milk Cooling System [5].*

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A no valve, flat plate solar ice maker was developed by Li *et al*. [7]. There were no valves and measure gauges installed on this advanced device, also, there were no moving parts on this device, activated carbon and methanol is used as working pairs for this no valve solar ice maker shown in Figure 8. The system could produce 4.0 kg ice and the COP solar was about 0.12 when the total insolation energy accepted by collector was about 16–18 MJ/m^2.

A new type of absorption refrigeration cycle that is co-driven both by solar energy and electricity was evaluated by Chen *et al*. [3]. The principle of a heat transformer was applied to the absorption refrigeration system to increase its efficiency. A compressor is added to the traditional absorption refrigeration system to give a new cycle as shown in Figure 9.

The COP, condenser heat load, the theoretical minimum evaporating temperature and refrigeration capacity for a typical daily load of the system were calculated and compared with those of traditional absorption refrigeration systems. The results show that the new cycle not only overcomes some shortcomings of the traditional absorption cycle with unsteady energy input from a variable source such as solar energy, but also increases the system's coefficient of performance.

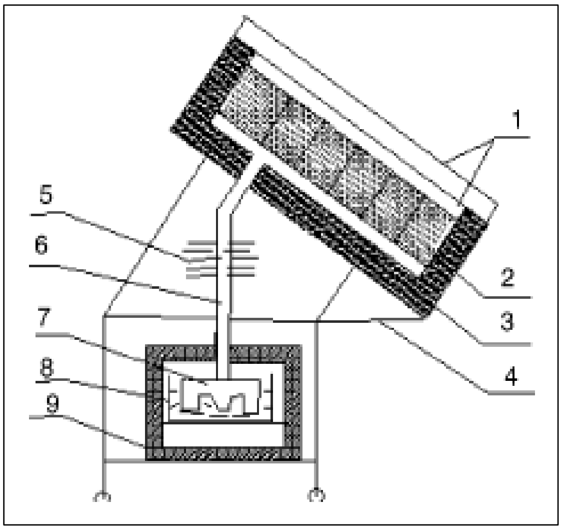

Fig. 8: *The Sketch Structure of the No Valve Solar Ice Maker: (1) Cover Plate, (2) Adsorbent Bed, (3) Insulation Materials, (4) Ice Frame, (5) Condenser, (6) Connecting Pipe, (7) Evaporator, (8) Water Tank, (9) Insulation Box [7].*

A hybrid system of solar-powered water heater and ice-maker as shown in Figure 10 has been developed by Wang *et al*. [13]. The system consists of a solar collector, water tank adsorber/generator, condenser, evaporator, receiver, ice-box, etc. The working principle is based on the combination of a solar water heater and an adsorption refrigerator.

In the morning, the solar collector heats the water tank and along with the increase of water temperature, the temperature in the adsorbent bed rises. In an ideal process, the adsorbent temperature could reach a level very close to the water temperature in the tank.

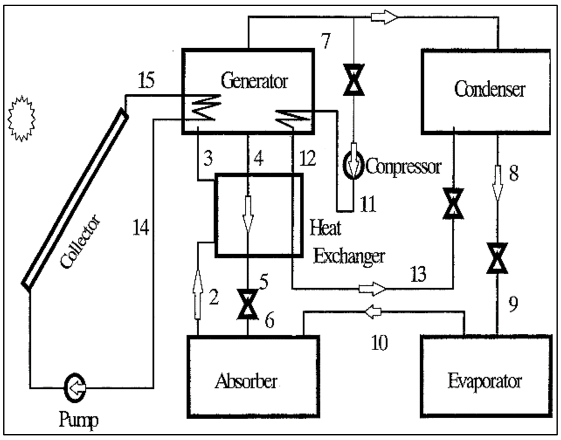

Fig. 9: *System Schematic for the New Refrigeration Cycle [3].*

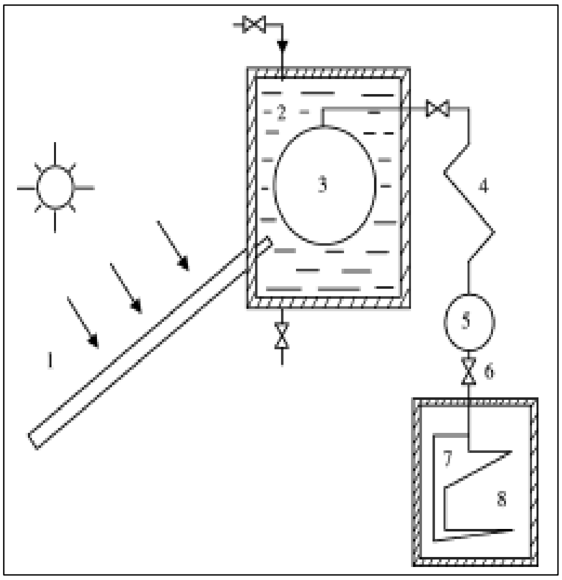

Fig. 10: *Schematic of the Hybrid System: (1) Solar Collector; (2) Water Tank; (3) Adsorber; (4) Condenser; (5) Receiver; (6) Valve; (7) Evaporator; (8) Refrigerator [13].*

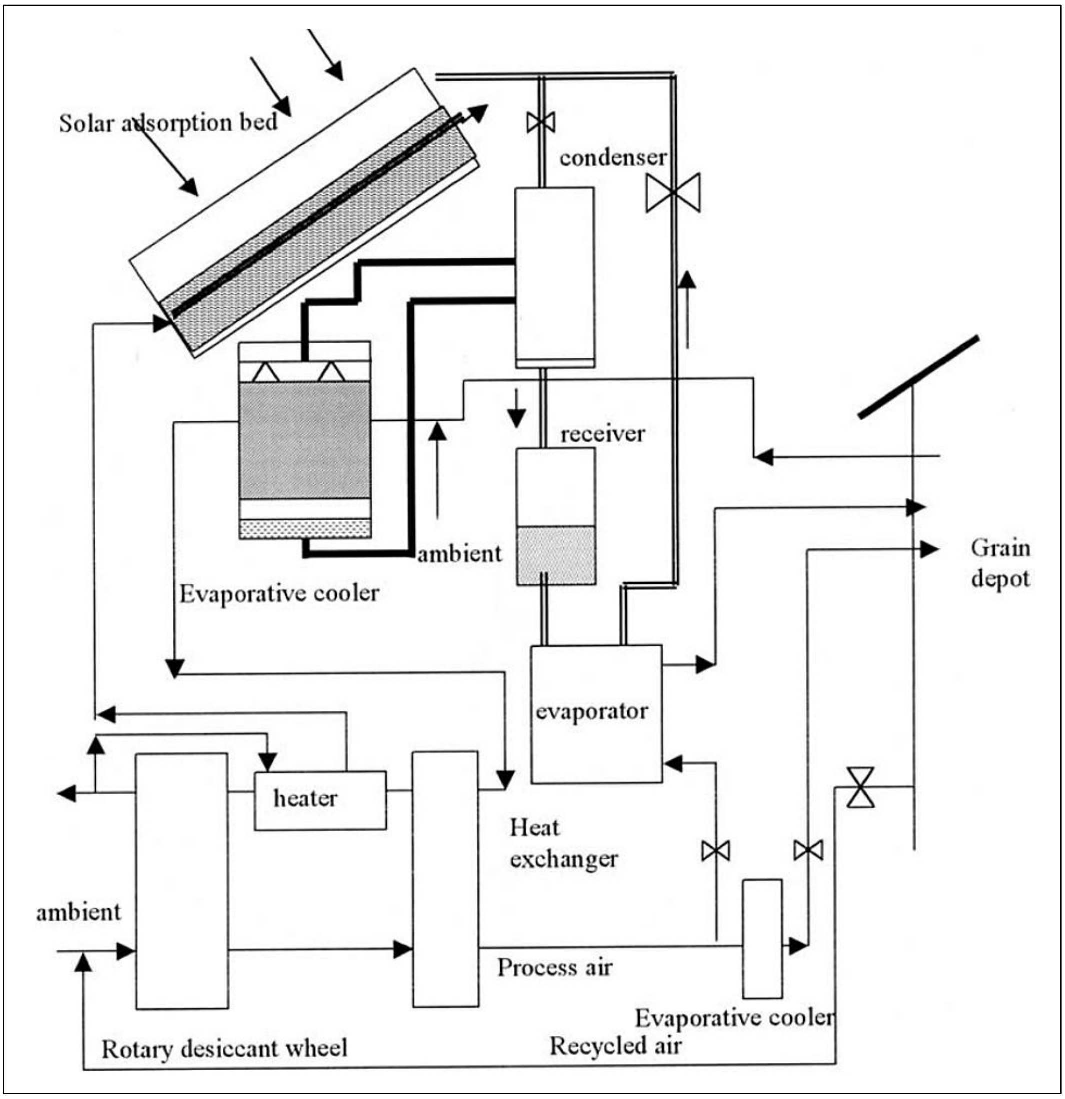

Fig. 11: *Schematic of the Solar Cooling System with Rotary Desiccant Dehumidification and Solar Adsorption Refrigeration [14].*

Dai *et al*. have investigated the performance of a hybrid solar cooling system as shown in Figure 11, which combines the technologies of rotary desiccant dehumidification and solid adsorption refrigeration, for cooling grain [14]. The key components of the system are a rotary desiccant wheel and a solar adsorption collector. The former is used for dehumidification and the later acts as both an adsorption unit and a solar collector. The heating load from sunshine can thus be reduced to a greater extent since the solar adsorption collector is placed on the roof of the grain depot. Compared with the solid adsorption refrigeration system alone; the new hybrid system performs better. A novel solar-powered adsorption cooling system for low-temperature grain storage has been built by Luo *et al*., which consist of a solar-powered water heating system, a silica gel-water adsorption chiller, a cooling tower and a fan coil unit in Figure 12 [6].

The adsorption chiller is composed of two identical adsorption units, each of them containing an adsorber, a condenser, and an evaporator/receiver. The chiller had a cooling power between 66 and 90 W/m2 of collector surface, with a daily solar cooling coefficient of performance (COP solar) ranging from 0.096 to 0.13.

NASA's Johnson Space Center have patented a solar-powered refrigeration system that eliminates reliance on an electric grid, requires no batteries, and stores thermal energy for efficient use when sunlight is absent as shown in Figure 13 [15].

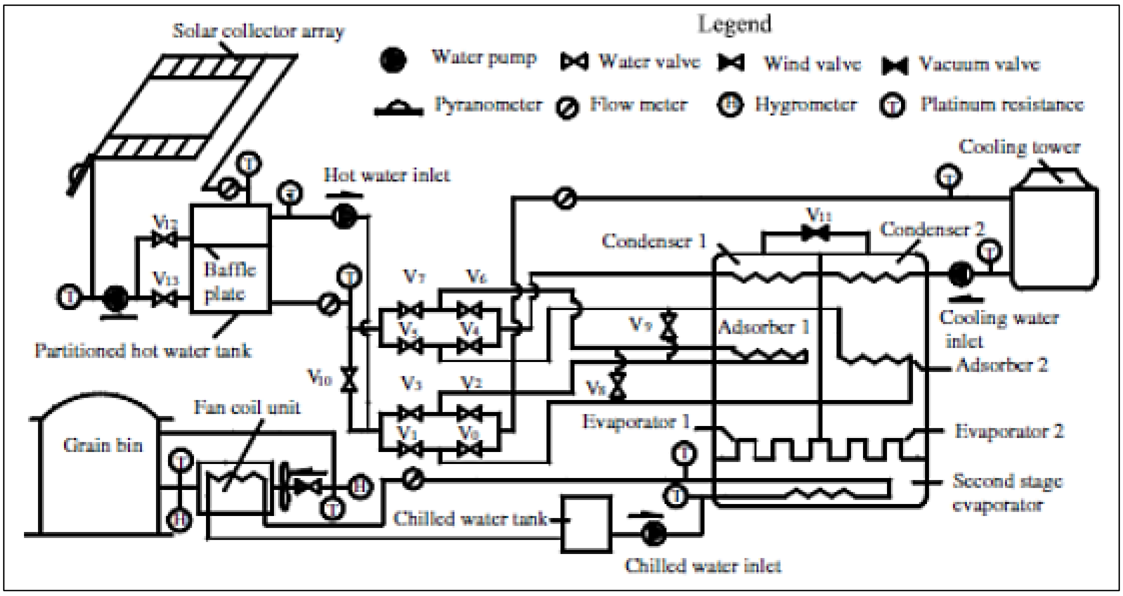

Fig. 12: *Adsorption Chiller for Storing Grain [6].*

Fig. 13: *NASA's Johnson Space Center Solar-Powered Refrigeration System [15].*

It is particularly suitable for off grid application Johnson Space Center's solar-powered refrigeration system employs a PV panel, vapor compressor, thermal storage and reservoir, and electronic controls. The process that makes the refrigeration possible is the conversion of sunlight into DC electrical power, achieved by the PV panel. The DC electrical power drives the compressor to circulate refrigerant through a vapor compression refrigeration loop that extracts heat from an insulated enclosure.

This enclosure includes the thermal reservoir and a phase change material. This material freezes as heat is extracted from the enclosure. This process effectively creates an "ice pack," enabling temperature maintenance inside the enclosure in the absence of sunlight.

Proper sizing of the highly insulated cabinet, phase change thermal storage, variable speed compressor, and solar PV panel allow the refrigerator to stay cold all year long. To optimize the conversion of solar power into stored thermal energy, a compressor control method fully exploits the available energy.

Solar-Operated Absorption Chiller

Absorption refrigeration system operating with solar energy was designed by Arias-Varela *et al.* [16]. This project was developed to determine a means of providing refrigeration to communities lacking conventional energy sources. The design of an absorption refrigeration system operating with solar energy was carried out. The refrigerator is used to conserve sea food in Figure 14.

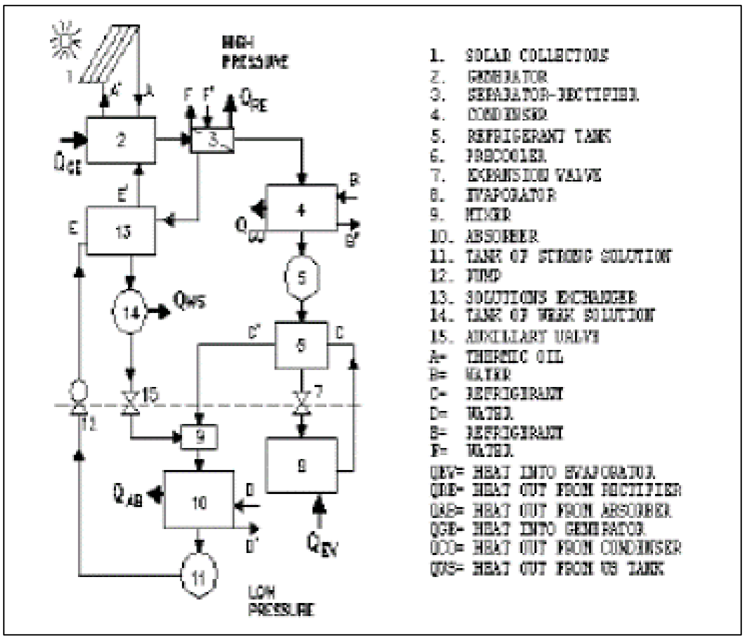

Fig. 14: *Components of Solar Absorption Refrigerator [16].*

The system is adapted to an industrial size cold-storage room. A maximum of 200 kg of fish in ice can be introduced to this room daily, up to a total capacity of 2 t. The lowest temperature the evaporator reaches is –10°C, the high and low system pressures are 13.4 and 2.87 atm respectively. The refrigerant-absorbent mixture is ammonia and water, where the refrigerant is ammonia. The design of this system requires six effective solar hours to generate the refrigerant needed by the refrigerator to work eighteen hours daily.

Hildbrand *et al.* built an adsorptive solar refrigerator in September 2000, in Yverdon-les-Bains, Switzerland [17]. The adsorption pair is silicagel + water. The machine does not contain any moving parts, does not consume any mechanical energy except for experimental purposes and is relatively easy to manufacture, as shown in Figure 15. Cylindrical tubes function as both the adsorber system and the solar collector (flat-plate, 2 m2 double glazed); the condenser is air-cooled (natural convection) and the evaporator contains 40 l of water that can freeze.

This ice functions as a cold storage for the cabinet (320 l). The first tests (September 2000) showed a very promising performance, with a gross solar cooling COPSR of 0.19. After minor modifications, a second test series was carried out during summer 2001.

This test series shows how the external parameters influence the machine with respect to the COPSR (irradiation and external temperature). The latter varies between 0.10 and 0.25 with a mean value of 0.16. These values are higher than those obtained by earlier solar powered refrigerators (0.10–0.12).

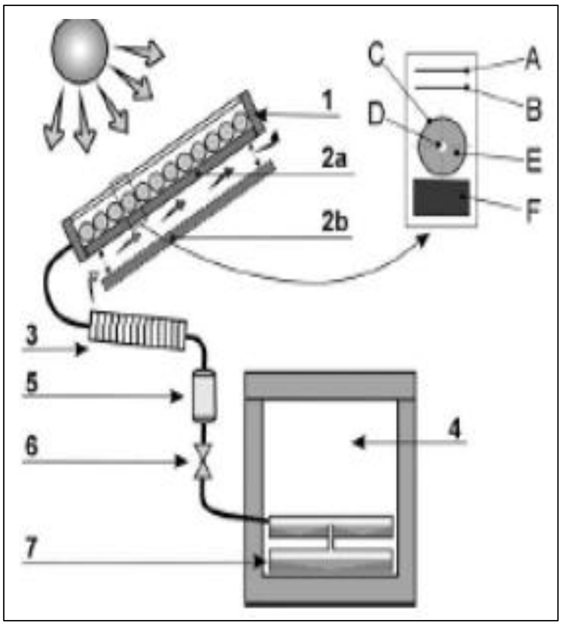

Fig. 15: *Solar Collector and Adsorber (1) Glass Cover: (A) Teflon Film, (B) Tube Covered with Selective Surface, (C) Central Tube for Vapour Transport, (D) Silica Gel Bed, (E) Thermal Insulation, (2) Ventilation Dampers; (3) Condenser; (4) Cold Box; (5) Evaporator and Ice Storage [17].*

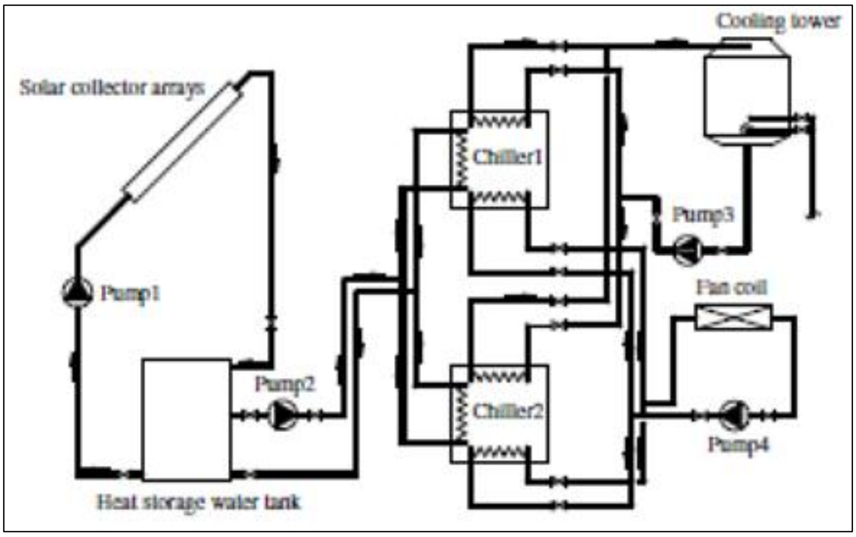

Fig. 16: *Flow Diagram of Solar Adsorption Cooling System [18].*

A solar adsorption cooling system was constructed in the green building of Shanghai Institute of Building Science by Zhai and Wang [18], as shown in Figure 16. The system consisted of evacuated tube solar collector arrays of area 150 m^2, two adsorption chillers with nominal cooling capacity of 8.5 kW for each and a hot water storage tank of 2.5 m^3 in volume [19–22]. A mathematical model of the system was established. According to experimental results, under typical weather condition of Shanghai, the average cooling capacity of the system was 15.3 kW during continuous operation for 8 h [23–25].

CONCLUSION

The advancement in solar refrigeration is most promising for rural and remote areas where conventional, electrically powered vapour compression refrigeration system may not be of much use as grid electricity is not presently available and not likely to be available in the near future due to huge financial outlays involved; so, solar cooling is the most promising alternative for essential application such as food and drugs preservations, alternative refrigeration systems are required, but still these systems are not commercialized. Each has its own unique problems, for example, in case of liquid absorption system, the need for solution pump and a rectifier for the vapor leaving the generator introduces unpleasant complications in the system design and also results in the performance reduction [26–28].

The major problem of the absorption system is the expansion of the absorbent upon the absorption of the refrigeration and both absorption and adsorption systems have low thermal conductivity. The initial absorption is rapid and then slows down towards the end. The major economic problem against the widespread utilization of solar cooling technologies is the costs of the units which are several times higher than those of conventional cooling technologies [29].

In spite of the foregoing problems limiting the widespread application of the solar cooling technologies, solar refrigeration and air conditioning can be expected to contribute significantly to the welfare of future generations in remote areas [30–31]. The solar refrigeration can be expected to play a significant role in meeting the needs of people in the rural areas of developing countries for refrigeration. The improvements required are mainly in the areas of increasing system performance and lowering costs [32]. With probable increase in the costs of conventional energy sources, it is expected that solar technologies will become competitive with the conventional system in future [33–36].

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