N80 23500

# FLUID CIRCULATING PUMP OPERATED BY SAME INCIDENT SOLAR ENERGY WHICH HEATS ENERGY COLLECTION FLUID[1]

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## ABSTRACT

This paper describes how a concept or idea for a solar-powered pump for spacecraft may be applied terrestrially to reduce or eliminate the need for fossil-fuel generated electricity for domestic solar hot water systems. A breadboard prototype model was constructed utilizing bimetals to convert thermal energy into mechanical motion by means of a toggle operated shutter mechanism. Although it did not meet expected thermal efficiency, the prototype model was sufficient to demonstrate the mechanical concept.

## INTRODUCTION

If a domestic hot water system has a rooftop solar thermal energy collector, it will likely require some method or means for pumping the solar heated fluid to the heat exchanger, storage tank, or other work-extracting device. Existing fluid pumps are usually operated by electricity which is generated mainly by burning fossil fuels. Most pumps require only a small amount of electrical power to operate the individual collectors. However, in view of the expected increase in rooftop solar energy collectors, the total annual power consumption in the aggregate may become significantly large enough to warrant considering any means of reducing the need in the United States for scarce costly fossil fuel generated electrical power.

A flow diagram for a rooftop solar thermal energy collection system is shown in Figure 1. A desired power source would be the same incident solar energy which is, during daylight hours, irradiating and heating the fluid in

[1]This paper presents one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS7-100, sponsored by the National Aeronautics and Space Administration.

the rooftop collector. In a typical installation, the solar heater is mounted higher than the storage tank, and the pump is essential to move the hot water, which is less dense than the cold water, to the heat exchanger (eg, room heater), to the storage tank, or to another heat-extracting device (eg, air conditioning unit).

## SYMBOLS AND ABBREVIATIONS

Values and calculations are given in both the International System (SI) and US Customary units.

| | |
|---|---|
| $D$ | deflection of element in cm (in.) |
| $m$ | specific deflection |
| $P$ | load or force in N (ozf) |
| $\Delta T$ | temperature change in K ($^{o}F$) |
| $t$ | thickness of element in cm (in.) |
| $K_{DS}$ | strip deflection constant per K ($^{o}F$) |
| $K_{PS}$ | strip torque constant, $N/m^2$ ($oz/in.^2$) |
| $d_o$ | diameter of disk in cm (in.) |
| $d_i$ | diameter of hole in disk in cm (in.) |

## BACKGROUND OF PUMP CONCEPT

A pumping system, originally conceived as an aerospace method for circulating a cooling fluid to control temperatures within electronic bays of outer planet spacecraft, may be terrestrially applied (in accordance with the NASA Technology Utilization Program) to domestic solar hot water installations.

The basic concept underlying the solar pumping system was not using electrical energy, but instead converting the heat energy obtained from sunlight into mechanical work or kinetic energy. For space purposes, it was necessary for the spacecraft coolant fluid to be routed between the interior of the electronic bay and the thermal radiator on the shadow side of the spacecraft. The spacecraft approach, as evaluated and adopted, was an alternating thermodynamic cycle operation in which a heat absorber is first exposed to solar energy and then shielded (cooled) from Sun energy in order to produce a reciprocating motion or mechanical work. The spacecraft concept provided a self-starting demand pumping system completely independent of the conventional onboard spacecraft power systems which were subjected to widely varying power requirements and demands. The concept as proposed for a terrestrial device will result in an automated system (i.e., when the water is being heated, it is being pumped; and, conversely, when it is not being heated, it is not being pumped). A device of this type could operate a pump from the same incident solar radiation that is heating the water for a domestic solar water heater. The description below follows the original concept proposed as a solution to the outer planet spacecraft internal temperature-cooling circulation problem.

## DESIGN THEORY AND APPROACH

The solar pump concept essentially is an application (Reference 1) based upon the difference in radiant energy between a thermal heat source and a thermal cold sink, which may be one and the same at different times. This may be understood if the pump is thought of as a sink being exposed to a source. Then, after the absorption of heat, the pump is alternatively considered as the heat source. The concept or idea for using the thermal difference between source and sink posed three problems: first, developing a system to convert the radiant energy to mechanical energy; second, selecting a suitable material for the source-sink; and third, providing a method for a self-starting control of the source-sink. The first problem involves, of course, the fact that heat as a form of energy obeys the principle of energy conservation and may be transferred into mechanical work (and vice versa). The system to convert heat into work makes use of the transformation accomplished by heating a material and causing the material to do work as it expands. Several materials were considered for the energy conversion source-sink unit, such as solids, liquids, and gases used singly, hybridized, and, when appropriate, combined with the change of state. Examples of substances considered are alcohol, paraffin, Freon, ammonia, and bimetals.

The selection of a material was closely associated with the consideration of a mechanical configuration. Among the configurations evaluated were bellows, Bourdon tubes, helixes, springs, spiral coils, U- and S-shapes, and others which produce mechanical motion as a result of changes in temperature either directly or indirectly. A thermostatic bimetal was selected because of its heat flow characteristics, thermal properties (Table 1, Reference 2), mechanical configurations or shapes, the availability of the material, and the convenience for fabricating a breadboard prototype model. The most important characteristic of thermostatic bimetal is that it bends or deflects proportionally with temperature change within a broad operating range (i.e., the bimetal is a linear transducer). Such a bimetal temporarily changes shape when heat is absorbed and reverts to the original shape when cooled. Another broadly useful property of thermostatic bimetal is its ability to develop a force when deflection is inhibited. A bimetal element thus can produce both force and deflection and thereby perform mechanical work.

The third or control problem was solved by developing an over-the-center toggle device which would provide self-starting and full-on/full-off cycling of the source-sink system fields of view.

## PUMP SYSTEM FUNCTION

The mechanical approach for converting heat energy into reciprocating motion utilizes a series of bimetal elements that are alternately exposed to and shielded from sunlight. The bimetal elements will change shape when heated by the Sun, then return to their original shape when cooled. For this application, the Sun is the source; the pump elements are the sink. As the pump elements cool, they are now the source radiating the solar heat previously absorbed. Thus, the pump becomes a sink-source or source-sink, as the situation may be, and the alternations create a reciprocating motion that could power a pump.

From a functional standpoint, since the device converts the heat from solar radiation directly into reciprocating mechanical motion, the working cycle may be defined as composed of a power stroke and a return stroke. During the power stroke the pump elements pile is exposed to the heat source, thereby resulting in its expansion. The power stroke performs three functions: provides power for the pump, preloads the shutter escapement mechanism, and stores energy for the return stroke. At the end of the power stroke, the shutter escapement mechanism releases, thereby shuttering the solar radiation from the pump elements pile and initiating the return stroke. During the return stroke, the pump pile radiates its heat, returns to its initial position, triggers the shutters escapement mechanism, and commences the cycle again.

## CONFIGURATION

The solar-powered pump developed at the Jet Propulsion Laboratory, Pasadena, California, is composed of a series of bimetallic disk elements or units mounted on a metal spindle or brass rod (see Figure 2). The spindle is the heat-into-motion rod onto which are placed the Belleville units made of thermostatic bimetal individually formed in the shape of Belleville springs (Figure 3) with the low expanding side on the concave side. The disks are installed alternating on the rod, concave to concave and convex to convex. The perimeters of adjacent disks may be welded or snapped together with clips to form unitary elements. The left end of the disk assembly is anchored to a fixed rigid pump system frame structure, and the right is secured to a locking collar on the sliding spindle or drive rod adjacent to the return spring (see Figure 4). The diameter of the hole (see Figure 3) in the Belleville disk, 0.953 cm (0.375 in.), allows enough clearance, and the disk hole has been deburred so as to slide freely upon the center slide rod or spindle.

The action of the disk pile assembly is such that straight line reciprocating motion is effectively gotten from the expansion and contraction of the circular bimetalic element units. The thermal deflection of the disk pile assembly may be determined for the entire solar power unit. In order to provide a force of 26.7 N (newton) (96 ozf) over a temperature range of 338.7 K (150°F) to 366.5 K (200°F) and assuming the specific deflection m is 0.5 to provide for a minimum bimetal volume, the thickness of each disk t may be calculated, where $K_{DS}$ is $138.6 \times 10^{-7}$/K (0.000076/°F), $K_{PS}$ is $4.31 \times 10^{10}$ N/m$^2$ (100 000 000 ozf/in$^2$), $\Delta T$ is 27.8 K (50°F), and P is 26.7 N (96 ozf):

$$t = \sqrt{\frac{P}{4K_{DS}K_{PS}\Delta T(1 - m)}} \tag{1}$$

$$= 0.0903 \text{ cm} \quad (0.0355 \text{ in.})$$

The thermal deflection per each 0.0903-cm (0.0355 in.) thick disk under the design force may be calculated from

$$D \text{ per disk} = \frac{K_{DS}\Delta T \,(d_o^2 - d_i^2)m}{5t} \tag{2}$$

For the breadboard prototype model, $d_o$ is 3.81 cm (1.5 in.) and $d_i$ is 0.95 cm (0.375 in.). Therefore, D = 0.00573 cm (0.00226 in.) per disk.

If the design total deflection for the stacked disk assembly is 0.76 cm (0.3 in.), then the

$$\text{Total number of disks} = \frac{\text{Total deflection required}}{\text{Deflection per disk}} \tag{3}$$

$$= \frac{0.76 \text{ cm}}{0.00573 \text{ cm}}$$

$$= 133 \text{ disks.}$$

The straight-line reciprocating motion drive rod slides and actuates both a diaphram pump system and an over-the-center toggle flip-flop system which controls the shutter-drive for temperature cycling, and compresses a return spring.

As discussed in design theory and approach, the pump is alternately a sink and then a source. This temperature alternating cycle is controlled or produced by a movable aperture shutter/shield arrangement shown in Figure 5. Aperture shutter control is maintained by the over-the-center toggle device, with the drive rod or slide bar providing input to the toggle arm attached to the interconnected reflector surfaces. The over-the-center toggle device provides full-on/full-off cycling without a dead zone. The shutter reflectors are open to the function required (i.e., absorb or reject heat), and they will continue that function until reversal. Delay due to wear or increase in hysteresis will be accommodated by the overtravel inherent in the design. The aperture shutter/shield has a parabolic cross section of polished stainless steel (shim stock) for a reflective surface. The shutter reflector in the open heating (solid lines) position is receiving solar heat and directing it to the bimetal Belleville disks. The shutters in the cooling position (dotted lines) act as a thermal insulator from the Sun and serve as a reflector to re-radiate heat from the pile. The insulation is, in fact, a polyurethane styrofoam-type material which, when in the shuttered cooling position, blocks incoming radiation to the disk pile assembly so that it, in rapidly cooling, becomes a source of heat. The temperature differential causes the Belleville material to contract and expand, resulting in work motion.

## PROTOTYPE BREADBOARD MODEL

The JPL prototype breadboard model contains 132 disks, 3.81 cm (1.5 in.) in diameter; each are free sliding on a brass slide bar which actuates a diaphragm pump. The other end of the spindle bar is attached to the toggle mechanism that drives the shutter reflectors. The disk stack was preloaded with a return spring calculated to return the mechanism to the cold position and to provide pumping action on the return cycle. The reflectors are of a modified vee-trough type with a parabolic shape. The rotational axis was located through the longitudinal center of gravity of each reflector half. The breadboard model was configured with an opening aperture 12.7 cm (5 in.) wide and 45.7 cm (18 in.) long.

## PERFORMANCE ANALYSIS

The analysis of the Belleville disk thermopile incorporated the parameters of pump requirements, toggle and reflector operation, and mechanical efficiencies based on anticipated friction losses. The breadboard model was constructed to provide a proof of concept demonstration. While the model did demonstrate the thermal powered toggle actuated cycling operation, it fell short of the analytical performance, providing but half the output expected. A disassembly and inspection revealed several of the disks locking up rather than sliding on the spindle drive rod, reducing the pump's performance.

Figures 4 and 5 show side and end views of the breadboard model. The small model-size prototype contained all primary elements described together with an associated diaphragm-type water pump mounted on one end and driven by the slide spindle bar. Operating at a frequency of one complete cycle every 40 minutes, the model demonstrated the mechanical concept.

## CONCLUSION

The pumping concept, as originally proposed for maintaining thermal equilibrium within a spacecraft, has possible wide terrestrial application. As demonstrated by a breadboard prototype model, the integration of the solar-powered pump within a domestic solar hot water system may be a desirable method for pumping heated water from roof-mounted collectors to the storage tanks, reducing or eliminating America's need for fossil-fuel generated energy for this facility. It is felt that further R&D will improve the model's performance.

## REFERENCES


1. National Aeronautics and Space Administration. NASA Tech Briefs, "Solar-Powered Hot-Water System," Vol. 3, No. 3, Fall 1978, pp. 349-350.

2. Design Highlights. An Introduction to Thermostatic Bimetal Applications — for Designers and Engineers. W. M. Chace Company, 1630 Beard Avenue, Detroit, Michigan 48209.


TABLE 1. PROPERTIES OF CHACE THERMOSTATIC BIMETALS[a]

| Type | Useful Deflection Range K (°F) | Maximum Sensitivity Range K (°F) | Deflection Constant Through Maximum Sensitivity Range Strips $(K_{DS})/K$ (/°F) | Torque Constant Strips $(K_{PS})$ $N/m^2$ ($ozf/in.^2$) |
|---|---|---|---|---|
| Chase #2400 | 200 to 644 (-100 to 700) | 255 to 422 (0 to 300) | .00001386 (.0000076) | $4.3 \times 10^{10}$ (100 000 000) |

[a]Selected from Reference 2.

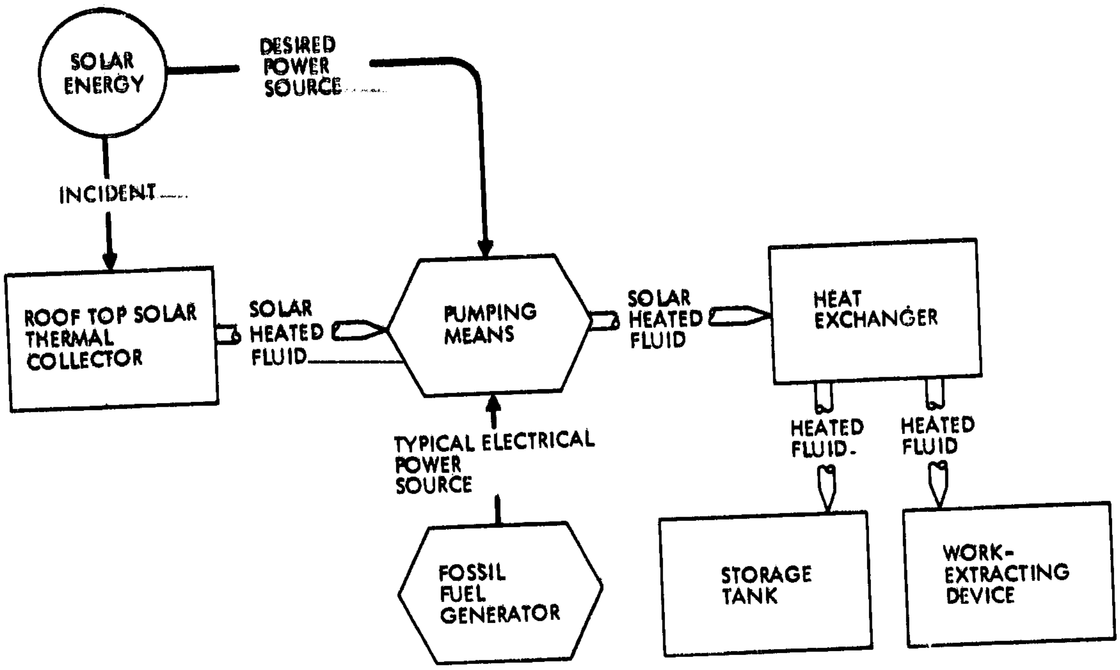


Figure 1.- Flow diagram for rooftop solar thermal energy collection system.

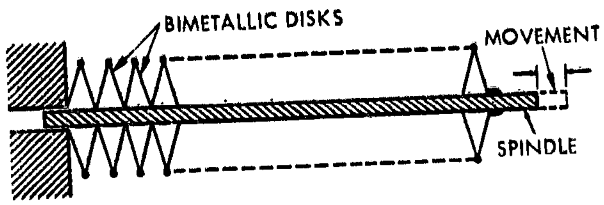


Figure 2.- Bimetallic disks linked together and joined to a spindle.

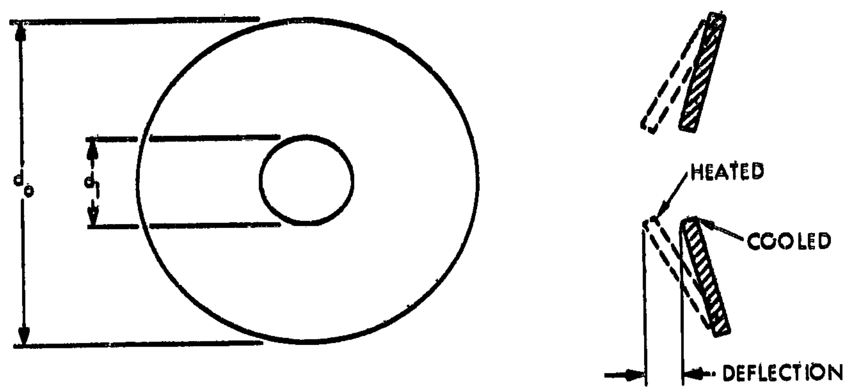


Figure 3.- Belleville spring disk deflection.

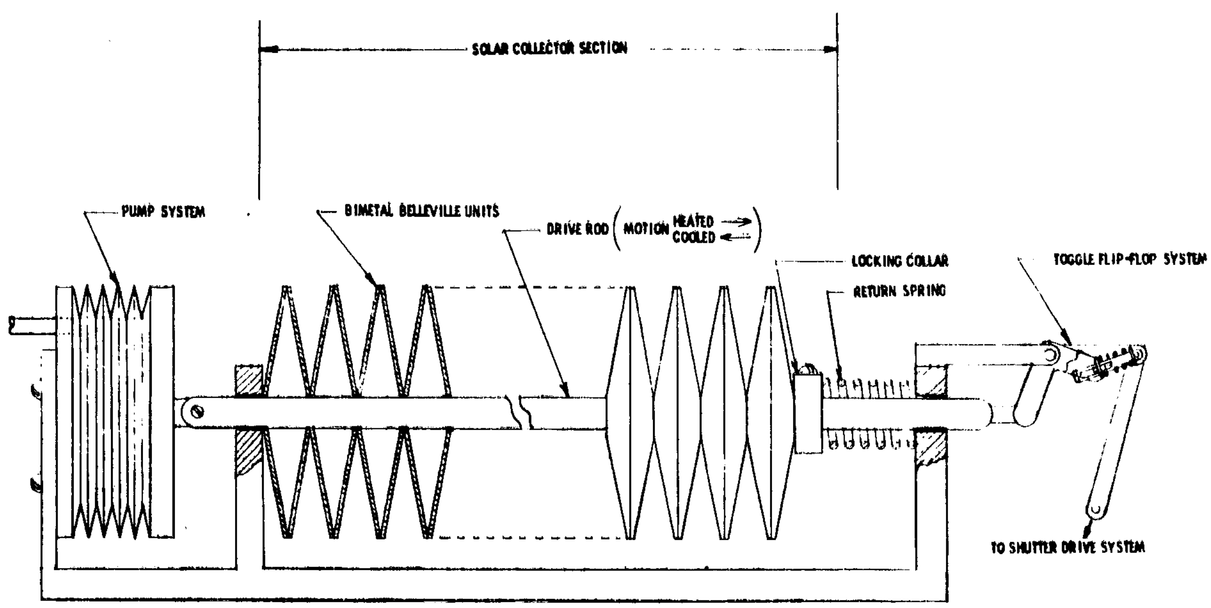


Figure 4.- Thermal pump side view, shutters removed.

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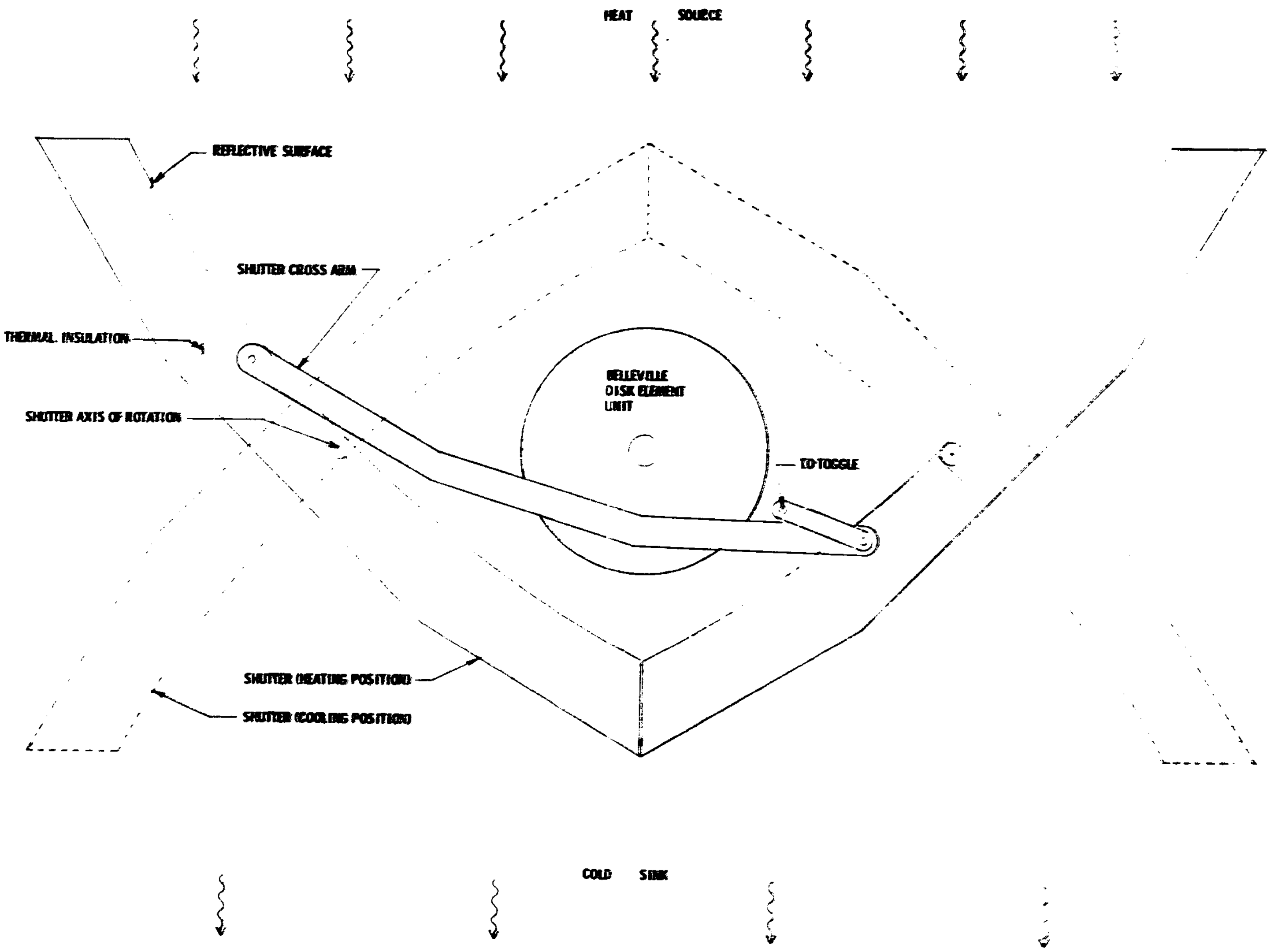


Figure 5.- Thermal pump solar collector system, end view.