SOLAR WATER HEATING SYSTEM FOR A LUNAR BASE

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This paper describes an investigation of the feasibility of using a solar water heater for a lunar base. During the investigation, computer codes were developed to model the lunar base configuration, lunar orbit, and heating systems. Numerous collector geometries, orientation variations, and system options were identified and analyzed. The results indicate that the recommended solar water heater could provide 88% of the design load and would not require changes in the overall lunar base design. The system would give a "safe-haven" water heating capability and use only 7% to 10% as much electricity as an electric heating system. As a result, a fixed position photovoltaic array can be reduced by 21 m^2.

INTRODUCTION

Hot water will be needed at a lunar base for various sanitation requirements such as dishwashing, clothes cleaning, bathing, and food preparation. The environmental control and life-support system (ECLSS) will also require a continuous and significant amount of heat for processing waste water. Typical hot water usage temperatures range from 40°C to 80°C. Electric water heating using a photovoltaic or solar dynamic array can be expensive and inefficient and can require intensive maintenance. Another important goal is to prevent loss of equipment or life during an emergency by providing a "safe-haven." This is an independently operating portion of the base (typically the habitat module) to which the personnel can retreat. Electric water heating systems could require unacceptably high power levels from limited auxiliary power systems during an emergency.

To avoid these problems, a solar water heater similar to a terrestrial system is proposed (Fig. 1).

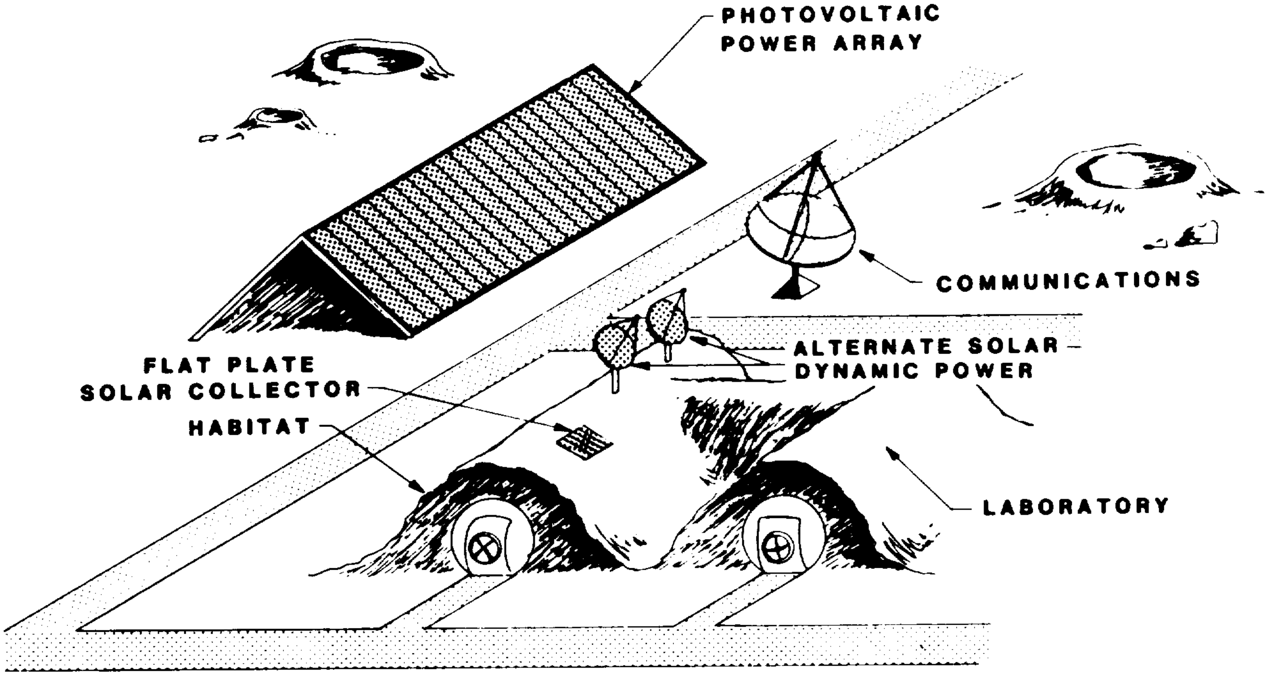

Fig. 1. Lunar base solar collector.

THERMAL MODEL

To investigate the proposed concept, computer programs were developed to assess the performance of candidate systems and the effects of system options. The external influences and internal processes of the lunar base are illustrated in Fig. 2 and listed in Table 1. TRASYS (*Jensen et al.,* 1977) was used to model the external effects, and a REMTECH program, QCOLL, written specifically for this purpose, was used to model the internal thermal processes.

External Influence Model

As indicated in Fig. 3, several types of collectors were modeled. A fixed position, flat plate collector and two types of variable position, concentrating or focusing collectors (dish and trough) were investigated. For reference during the investigation, the lunar base was modeled as two half-cylinders aligned east-west, similar to Fig. 2. The orientation of a collector to the sun determines the amount of incident energy. Obviously, the greatest incident energy occurs when the collector is perpendicular to the sun. In terrestrial applications, the collector must track the sun in two axes to obtain the maximum amount of energy because of daily and seasonal changes in the sun's position. For a lunar base, the situation is simpler because the Moon's equatorial plane is only tilted 1.5° to the solar ecliptic plane and therefore has no "seasons." By tilting a collector at an angle equal to the latitude of the lunar base, the collector can track the sun by rotating about only one axis during the lunar day. Traditional terrestrial applications, however, have shown that tracking the sun is unnecessary and that fixed position, flat plate collectors work well. Terrestrial applications have also shown that even when flat plate collectors are positioned relatively far from the optimal tilt and due south (northern hemisphere) azimuth, they still perform well. To determine effects of tilt and azimuth, the following cases were run

Case ID	Latitude	Tilt	Azimuth
L 000*	0°	0°	0°
L 400	45°	0°	0°
L 430	45°	30°	0°
L 440*	45°	45°	0°
L 434	45°	30°	45°
L 444	45°	45°	45°

* Denotes optimum condition for that latitude.

TABLE 1. External and internal parameters.

External Influences	Internal Processes
Configuration • Shapes and position of collector and adjacent structures • View factors to adjacent *Orientation* • Orbital mechanics of Moon • Location, tilt, and azimuth on Moon • Angle of collector at any time to sun *Energy* • Direct solar and albedo • Direct and reflected IR	*Collector* • Type of system (plate or concentrator) • Size • α and ϵ • Pumped fluid or heat pipe • Flow properties (rate, laminar flow) • Piping size and material properties (κ, c_p, ρ) • Heat balance (solar absorption-IR emission) *Storage* • Volume • Heat exchanger (pumped fluid) • Heat balance (solar energy added-energy to load) *Demand Load* • Time and duration of loads • Simultaneous multiple loads • Temperature of loads

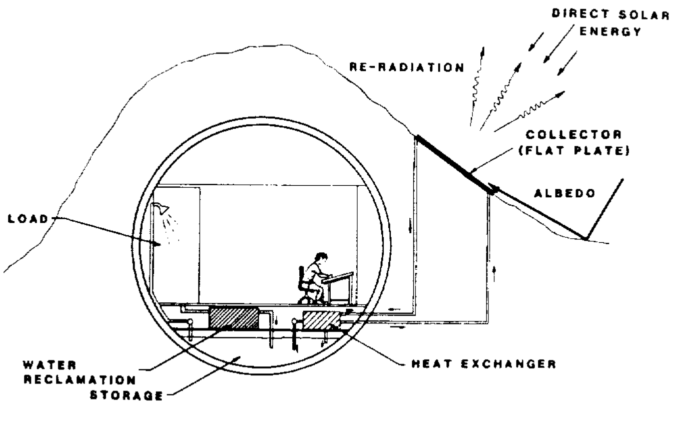

Fig. 2. External and internal conditions modeled.

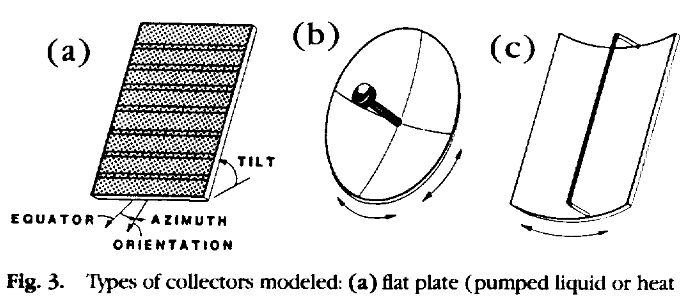

Fig. 3. Types of collectors modeled: **(a)** flat plate (pumped liquid or heat pipe; **(b)** two-axis tracking dish; **(c)** one-axis tracking trough.

The effect of tilt can be seen in Fig. 4 where the incident energy for each due south (0° azimuth) orientation is plotted. The plots start at lunar midnight, so no energy is received until approximately seven terrestrial days later. The incident energy increases until solar noon (approximately 14 days) and then decreases as the sun sets. For tilt, the worst case shown is the L 400 where the collector at a 45° latitude is flat on the surface. Approximately 60% of the ideal case incident energy is incident on this collector. By tilting the collector to 30° (L 430), the incident energy is increased and is only about 5% less than the optimum L 440. The optimum at 45° latitude, L 440, and the optimum at 0° latitude, L 000, are equal because they both have the same orientation to the sun.

Figure 5 shows the effect of azimuth. Here, the collectors pointed 45° to the east peak two to four days sooner and received 95% as much energy as the collectors pointed due south (northern hemisphere is assumed). It is seen, therefore, that the lunar fixed position, flat plate collectors follow the same trend as terrestrial collectors in that they collect energy at near optimum levels even when positioned considerably off the optimum tilt and azimuth.

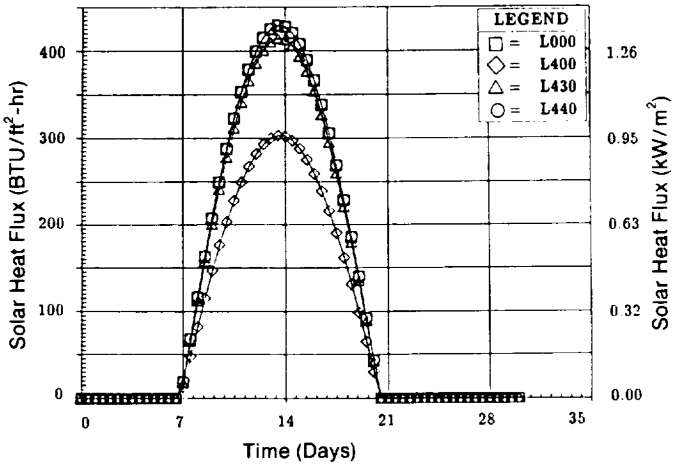

Fig. 4. Effect of collector tilt on incident solar energy.

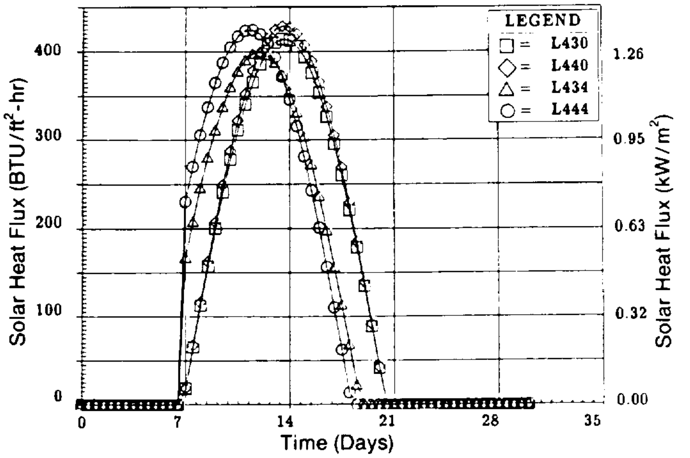

Fig. 5. Effect of collector azimuth on incident energy.

The incident energy for the dish and trough concentrators is constant, since they track the sun. Essentially, they receive the solar constant, 1352 W/m^2 (429 Btu/hr-ft^2) during the daylight hours, which is the maximum possible amount of solar energy available. The integrated total energy value is approximately twice that of the fixed position, flat plate at optimum orientation.

Internal Processes Model

The first step in modeling the internal processes was to establish the hot water usages and express them as a profile of the demand heating load. The plot shown in Fig. 6 is based on the loads shown in Table 2, which gives each assumed load and delivery temperature for an eight-person operation. These loads may change in the future, but the plot shown is the current estimate.

Two internally different collector systems were investigated and were modeled separately. The first, shown in Fig. 7a, uses a pumped liquid as the heat transfer medium. Since the liquid must not boil or freeze in the collector, the direct use of water was ruled out. Therefore, the liquid is pumped through a separate, collector/heat exchanger closed loop. In the meantime, water is pumped from storage through the heat exchanger and returned. The collector can be either a plate or a concentrator.

In the second system (Fig. 7b), the collector is a plate to which heat pipes have been attached. A heat pipe is a closed tube filled with a substance in its liquid and vapor phases. Heat on one portion of the tube evaporates the liquid and causes a higher vapor pressure in that portion. The vapor flows to the lower pressure areas of the tube where it is cooled and it condenses, thus perpetuating the low pressure. The liquid thus condensed flows by capillary action back to the heated region in small tubes placed in or under the heat pipe or meshes and grooves cut inside the heat pipe. In the heat pipe system model, the storage water is pumped from storage through a heat exchanger; this portion of the model coincides with the pumped fluid model.

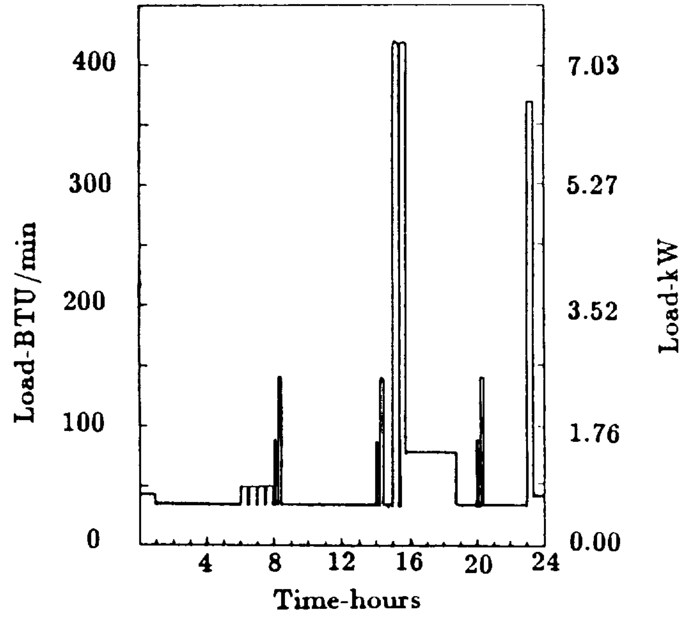

Fig. 6. Demand heating load.

TABLE 2. Individual demand loads for lunar base.

Demand	Occurrence	Amount	Time	Temperature
Handwashing[*,†,‡]	24	0.61 kg (1.35 lb)	1 min	41°C (105°F)
Showers[*,†,‡]	4	3.60 kg (8 lb)	18 min	41°C (105°F)
Potable[*]	3	6.89 kg (15.2 lb)	10 min	74°C (165°F)
Dishwashing[*,†]	1	43.50 kg (96 lb)	20 min	60°C (140°F)
Clothes Washing[*,§]	2	49.90 kg (110 lb)	20 min	66°C (150°F)
Dish Drying[§]	1	150 W	1.5 hr	38°C (100°F)
Clothes Drying[§]	1	750 W	3 hr	66°C (150°F)
Water Recovery[*]	Continuous	300 W		54°C (130°F)
Water Recovery[*]	Continuous	300 W		82°C (180°F)

[*] R. Bagdigion, personal communication.
[†] *ASHRAE*, 1984.
[‡] R. Garcia, personal communication.
[§] D. Schiller, personal communication.

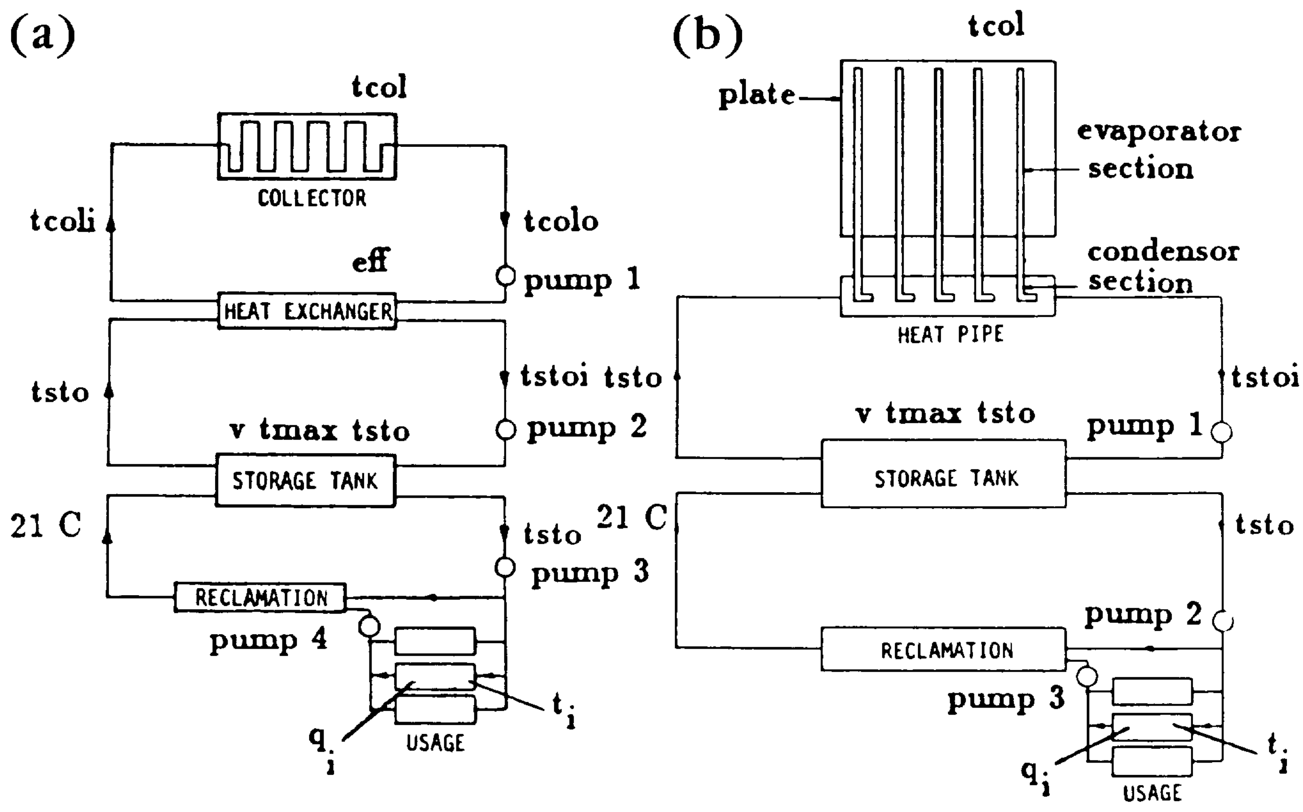

Fig. 7. System models for the internal processes: (a) pumped fluid or concentrator system; (b) heat pipe collector system.

The computer models for each system perform energy balances on all components at approximately two-minute intervals in the lunar day. Normally the run time simulated 1440 hr of activity on the lunar base. The first 720 hr allowed the system to reach steady state, and a normal operation cycle could then be observed for the second 720 hr. Generally, the pumps are predicted to run continuously during the lunar day (~14 terrestrial days). However, if the storage temperature becomes 93°C, the pumps are "turned off" by the model and excess heat reradiates to space.

PERFORMANCE

The methodology used for determining system performance and comparing options consisted of three steps. Initially, a baseline system was established. This was based on terrestrial experience and iteratively running the program for some of the options. A pumped fluid, flat plate collector system that heated 100% of the demand hot water with solar energy was chosen. Next, three variations of each option were simulated using the appropriate computer model. In the final step, t_{sto}, SFT, η, and other parameters were compared to the baseline to determine whether the options being studied had a serious impact on system output.

Figure 8 is an example of a comparison between various values of α and ϵ. The t_{sto} was computed for the baseline ($\alpha = 0.80$, $\epsilon = 0.20$), for improved values ($\alpha = 0.96$, $\epsilon = 0.12$), and for a near-black body ($\alpha = 0.96$, $\epsilon = 0.96$). Note that in an ideal collector $\alpha = 1.00$ and $\epsilon = 0.00$, which means all energy is absorbed and none is reradiated. Only minor improvement is seen using the improved values, but a marked decline in t_{sto} and SFT is evident for the near-black body. The effect of all options is summarized qualitatively in Table 3.

Once the influence of each option was understood, no more work was done with those found to be negligible, and only the collector size and storage volume impacts were studied further. This study produced a series of "design curves" by which a designer can make quick trade-off studies.

Figure 9 shows the design curves for a pumped fluid collector. The SFT has been plotted as a function of collector area and storage volume. As expected, SFT increases as the collector size increases. This occurs regardless of the storage size up to ~2 m². The explanation for this phenomenon, which was seen in the design curves for all systems, is that the collector is too small to supply the total load. The collected energy is used almost immediately, leaving little or none to be stored; thus, little storage is required. Beyond the 2 m² point, additional energy is available after the demand has been satisfied; therefore, storage must be larger to accommodate it. If the collector size is increased beyond 4.5 m², little change occurs in SFT unless the storage volume is increased.

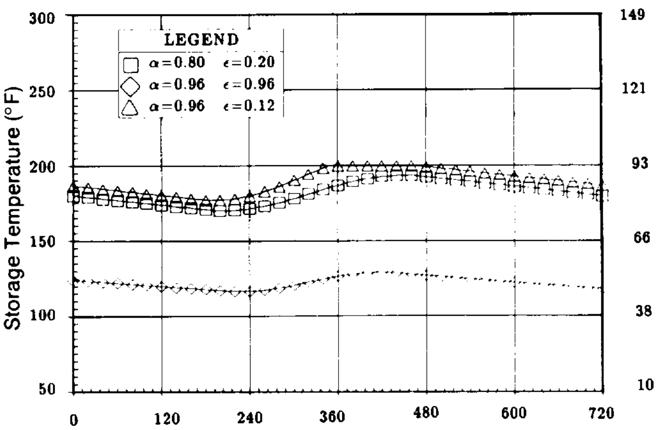

Fig. 8. Effect of absorptivity and emissivity.

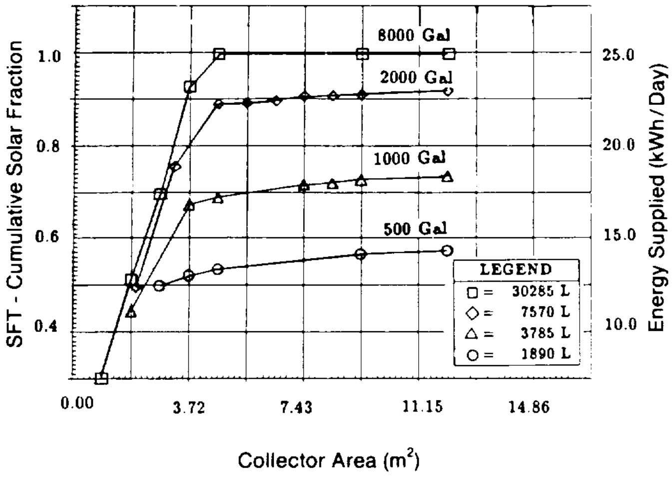

Fig. 9. Design curve for flat plate pumped fluid system.

TABLE 3. Effect of options on system performance.

Significant Effect	Negligible Effect
• Collector Size	• Fluid Type and Flow Rate
• Plate or Concentrator	• Collector Tilt and Azimuth (within 20°)
• Storage Size	• Heat Pipe or Pumped Fluid
• Coating α and ϵ	• Heat Exchanger Efficiency (within 0.5 to 0.8)

It can be seen that the storage volume is very large compared to the collector area. This large volume is required because of the exceptionally long night during which no solar energy is available to replace tank energy losses caused by water usage.

RECOMMENDED SYSTEM

To provide ~100% of the demand load with a solar system would require a minimum area of 4.5 m² (50 ft²) of pumped liquid or heat pipe, flat plate collector, or 2.3 m² (25 ft²) of dish or trough concentrator. Because the concentrators track the sun and thus could cause maintenance problems, and because the flat plate area is so modest, it is recommended that the flat plate be used. The heat pipe collector offers a major advantage in that a micrometeoroid strike would only rupture one of the heat pipes, but the others would continue to function since they are closed units. Rupture of a pumped liquid line would cause a shutdown of the entire system until the line was repaired. The heat pipes in a collector, however, must be carefully leveled horizontally to prevent a gravity gradient or they will not function properly. They also have a major disadvantage, since under no-load, high-solar input conditions they will boil, creating pressure that can burst the pipes. The pumped fluid system operates the same regardless of tube alignment and can be drained to avoid boiling or freezing. Therefore, the recommended system collector is a 4.5 m², pumped liquid, flat plate. The coating would have $\alpha = 0.80$ to 0.95 and $\epsilon = 0.10$ to 0.20.

To achieve ~100% solar contribution, our model predicts that the storage must contain a minimum of 30,000 l (8000 gallons) of water (Fig. 9). Although water may well exist as ice on the Moon (*Staehle*, 1983) or may be produced by burning hydrogen, an initial eight-man base would probably not have this ability. The tank and water would have to be transported from Earth; therefore, 30,000 l of water and the tank for storing it are probably impractical due to cost. The model also predicts that if the storage volume is reduced by 75% to 7500 l (2000 gallons), the solar contribution only drops 12% (SFT = 0.88). This is still a large contribution for a modest-sized system, so the smaller volume is recommended.

The recommended system would have the following impact on delivery to and installation at the lunar base

Mechanical

Collector Area:	4.5 m^2 (10 cm thick)	Weight: 86 kg
Storage Volume: (See below)	7.6 m^3	Weight: 7557 kg
Auxiliary Equipment Volume:	0.2 m^3	Weight: 80 kg
Total Volume:	8.3 m^3	Total Weight: 7723 kg

Electrical

Total power to operate equipment: 175W

Coefficient of performance (Useful Energy/Operating Energy): 10.5

Reduction of fixed photovoltaic array ($\eta = 10\%$): 21 m^2

The above assumes that no hot water storage was necessary before the addition of this system. This is not true, though the exact amount is not known. An estimate would be 760 to 1180 l (200 to 300 gallons). This amount should be subtracted from the impact of the system storage volume and weight, reducing them by 10% to 15%. Another consideration that partially offsets this large storage volume and weight penalty is that backup and stored electricity systems can be considerably decreased. The amount would be dependent on the type of electric storage system, but the reduction of weight and volume of fuel cells, for example, would be significant and make the solar system more attractive.

CONCLUSIONS

The thermal analysis has shown the following:

1. A heat pipe or pumped fluid flat plate collector of ~4.5 m^2 is well suited for satisfying up to 100% of the assumed hot water demand.
2. The volume of storage water required to allow significant solar contribution would be very expensive if transported from Earth.
3. A concentrator would need only 50% as much area as a flat plate; however, it could be more difficult to transport and maintain.
4. The size of the photovoltaic array and backup and electricity storage systems can be significantly reduced compared to an electric water heater.
5. Except for storage volume the system has only a minor effect on the base design.

The overall conclusion is that a solar water heater for a lunar base is feasible and even desirable.

NOMENCLATURE

c_p = Specific heat
eff = Heat exchanger effectiveness
k = Conductivity
q_i = Heat load required by ith device
SFT = Solar fraction total (heat supplied to load by solar energy/heat load)
t_{col} = Collector temperature
t_{coli} = Fluid temperature entering collector
t_{colo} = Fluid temperature exiting collector
t_i = Delivery temperature required by ith device
t_{max} = Maximum temperature of storage
t_{sto} = Water temperature in storage
t_{stoi} = Water temperature entering storage
V = Storage volume
α = Absorptivity in solar spectrum
ϵ = Emissivity in infrared (IR) spectrum
η = Thermal efficiency of system (heat supplied to load by solar energy/incident solar energy on collector)
ρ = Density

REFERENCES

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Staehle R. L. (1983) Finding 'Paydirt' on the Moon and Asteroids. *Aeronaut. Astronaut.*, 44-49.