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# Thermochemical Energy Storage for a Lunar Base

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## THERMOCHEMICAL ENERGY STORAGE FOR A LUNAR BASE

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### ABSTRACT

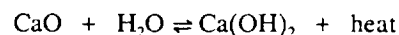
A thermochemical solar energy storage concept involving the reversible reaction  $\text{CaO} + \text{H}_2\text{O} \rightleftharpoons \text{Ca}(\text{OH})_2$  is proposed as a power system element for a lunar base. The operation and components of such a system are described. The  $\text{CaO}/\text{H}_2\text{O}$  system is capable of generating electric power during both the day and night. Mass of the required amount of  $\text{CaO}$  is neglected since it is obtained from lunar soil. Potential technical problems, such as reactor design and lunar soil processing, are reviewed.

### INTRODUCTION

A permanently manned moon base powered by solar energy will require a large storage system because of the 14 day long lunar night. Many types of storage systems have been proposed, such as regenerative hydrogen/oxygen fuel cells, Ni-H batteries, flywheels, and superconducting inductors, in addition to beamed power (Personal communication from David J. Bents of NASA Lewis Research Center, Cleveland, Ohio, 1990). The choice of storage system will be based on many factors including, but not limited, to specific energy (energy to mass ratio), energy conservation efficiency, lifetime, maintenance, and cost. Specific energy is likely to be the most important factor because of the high cost of transporting materials from the Earth to the Moon. Considerable improvements in the specific energy might be achieved by using raw materials that are found on the moon.

Thermochemical storage systems have been examined in recent years for solar energy storage on earth.<sup>1-5,17</sup> In these systems, solar energy is stored as the heat of reaction of a reversible chemical reaction. One example is the reaction of water with calcium oxide, producing calcium hydroxide and large amounts of heat:

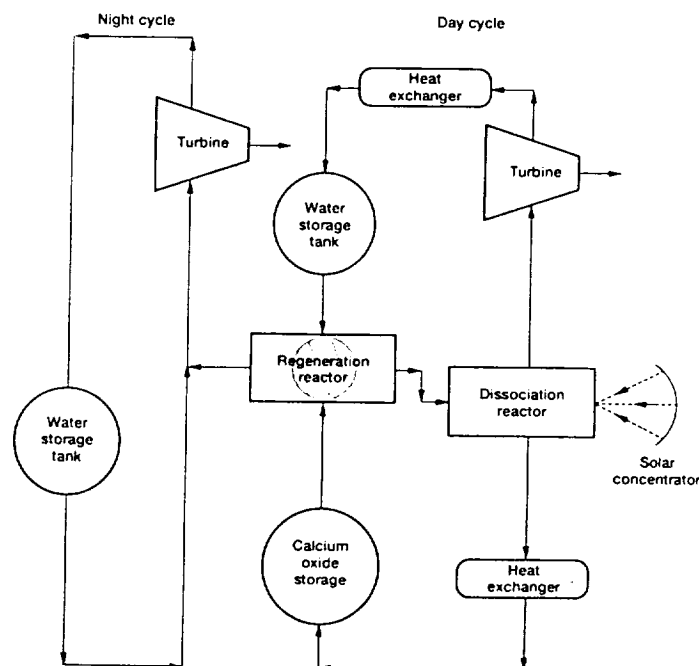
\*Summer Student Intern at NASA Lewis Research Center.



The fact that  $\text{CaO}$  is a major constituent of lunar soil (9-16%)<sup>6</sup> singles out this reaction as a possible solar energy storage system for a moon base.

### PROCESS DESCRIPTION

In the proposed thermochemical system direct solar radiation incident on a concentrator is directed onto a reactor (heat receiver), similar to the proposed by Werekobrobby<sup>17</sup>, Figure 1. The calcium hydroxide inside the

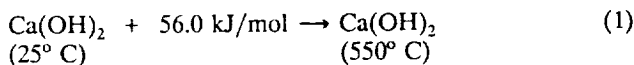


receiver is dissociated at a temperature of 500-550° C to generate steam and solid calcium oxide. The steam is circulated through a turbine to generate electrical power. The calcium oxide is passed through a heat exchanger to reduce its temperature to ambient and is stored at 25° C. When required, CaO and H<sub>2</sub>O are combined, initiating the chemical reaction and the heat of reaction is liberated. The heat liberated during recombination is used during the night in the secondary electric power generation system.

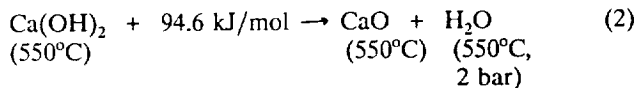
## SYSTEM CALCULATION

### Chemical Reaction

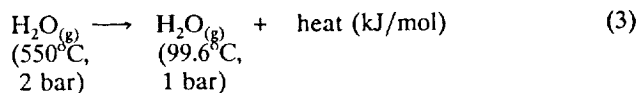
There are two types of energy storage involved in this reaction: sensible heat (heating from 25° C to 550° C) and heat of reaction. The reaction is reversible, and the chemical cycle can be divided into charging reactions (daytime) and discharging reactions (nighttime). During the day, solar energy is used to heat the Ca(OH)<sub>2</sub> to the dissociation temperature (510° - 550° C), and dissociate it producing CaO and steam (which is condensed and stored as liquid water) in accordance to the following charging reactions:



The amount of energy needed to heat calcium hydroxide from 25° to 530° C<sup>7</sup> is 56 kJ/mol.



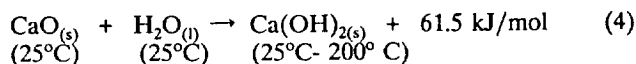
The heat of reaction for the above in the temperature range 530° to 800° C was calculated by Samms & Evans<sup>8</sup> to be 94.6 kJ/mol.



The energy released by reaction (3) is used to generate electrical power by use of a steam turbine.<sup>9</sup>

During the lunar night, the water is brought in contact with the CaO, forming Ca(OH)<sub>2</sub> and releasing large amounts of energy, which can be used for a secondary electrical power generation:

The discharging reaction<sup>7,10</sup> is given by:



The heat liberated during recombination is used in a heat exchanger for heating a low temperature working fluid, steam. The low temperature steam is passed through a turbine to generate electric power.

Many charge/discharge cycles will be required during the lifetime of the system; hence side reactions with

impurities and container materials must be minimized to insure high reversibility of the CaO/H<sub>2</sub>O reaction. The major side reaction of concern for CaO/H<sub>2</sub>O solar energy storage systems on earth is the reaction of CaO with carbon dioxide:



forming CaCO<sub>3</sub>, which has a higher dissociation temperature (898° C). On the moon, however, this should not be a problem because of the lack of CO<sub>2</sub>. Investigations have shown that the degree of reaction completion is 94-99% after over 1100 hydration/dehydration cycles if the formation of CaCO<sub>3</sub> is not taken into account.<sup>1,11</sup> Another potential side reaction is the formation of non-condensable gases (mainly H<sub>2</sub>) if a corrosion reaction with a stainless steel container occurs.<sup>1</sup>

A major concern for CaO/H<sub>2</sub>O storage systems on earth is the time required for reaction completion. This can be influenced by reactor design. Several experiments have been performed using the metal fins to improve heat transfer in the powdered CaO and Ca(OH)<sub>2</sub>, which have a low thermal conductivity.<sup>5, 7, 12, 13</sup> Reaction times were typically about 2 hours or less.

Reactor pressure is a parameter which can be controlled for system optimization. The dependence of the dissociation temperature on pressure is shown in Figure 2.<sup>8</sup>

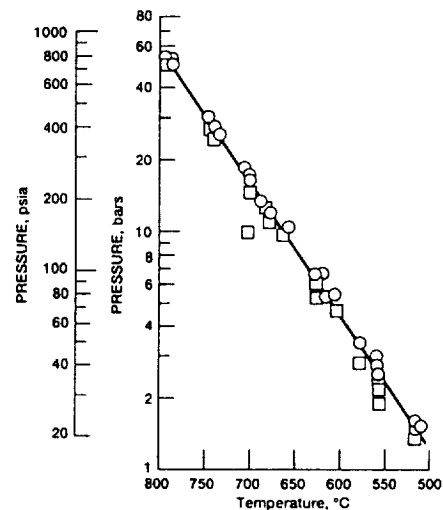


Figure 2.—Pressure versus dissociation temperature for CaO + H<sub>2</sub>O → Ca(OH)<sub>2</sub> (ref. 8).

Having the reactor at a higher temperature and pressure would allow higher efficiency, but it would also require an increased reactor wall thickness (and mass) to withstand higher pressures. This is a trade-off which would have to be considered in designing the reactor.

In order to estimate the solar collector area and flow rate required to produce a 100 KW<sub>e</sub> power generation system to operate on the lunar surface, the following was assumed:

- a- thermal energy storage-system efficiency of .84;<sup>4</sup>
- b- the solar collector weighs 1.5 kg/m<sup>2</sup>
- c- the steam turbine specifications are: 500° C, 40 bar, turbine efficiency of 80 %, steam quality of .95 (day cycle); 220° C, 2 bar (night cycle)

The energy and mass balance for a 100 kW system based on the above assumptions are presented in Figure 3.

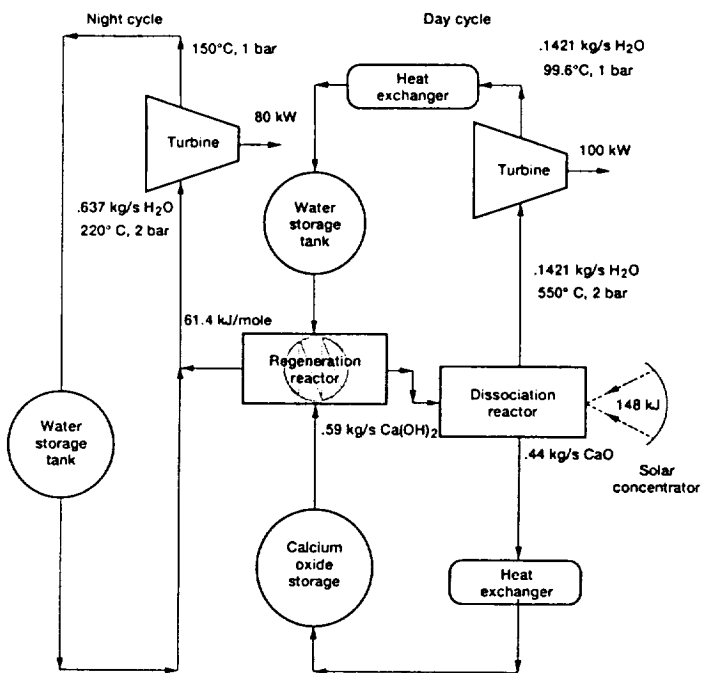


Figure 3.—Energy and mass balances for 100 kW system.

### Reactor Design

The reactor design recommended for this noncatalytic reaction is a continuous (moving bed) reactor.<sup>13</sup> There is direct heat transfer between the reacting solids and the gas. A shrinking core model<sup>14</sup> (endothermic side) and the following were assumed in order to estimate the solids residence time and reactors size.

- a- the residence time is the same for all solid particles;
- b- the H<sub>2</sub>O vapor concentration is constant throughout the reactor;
- c- solid particles are uniform in size, 1 mm;

The necessary estimated solids residence time based on the above assumptions is 1.5 minutes for the proposed systems, the reactor size calculations were made using twice this estimated time.

### Specific Energy

For purpose of calculation of the specific energy, a system providing 100 kW of electricity during the lunar night (and 123 kW during the lunar day) will be assumed. The lunar night is 350 hours; hence  $1.26 \times 10^8$  kJ of electrical energy are needed, which corresponds of 179, 748 kg of H<sub>2</sub>O. Also, 559, 216 kg of CaO will be needed, but it will be processed from the lunar soil and not brought from Earth.

The estimated masses of other components, for a 100 kW<sub>e</sub> system, which need to be brought from earth are listed below.

Components	Mass (kg)
Solar concentrator	981
H <sub>2</sub> O tanks	917
Reactors	695
Radiator	433
Power management and distribution	400
Heat exchangers	17
Subtotal	3443
Water	969,348
Total	972,791

The reactor construction material recommended is Inconel (density of 8.3 g/cm<sup>3</sup>). The system produces 105 kW of electricity. The extra 5 kW are used to run the pumps needed in the system.

The specific energy is calculated based on the energy per mass of materials transported from Earth:

$$\text{specific energy} = \frac{\text{energy}}{\text{mass}} = \frac{(100 \text{ kW})(350 \text{ hr})}{9.73 \times 10^5 \text{ kg}} = 36 \frac{\text{W-hr}}{\text{kg}}$$

This number can be compared to the specific energies of more familiar energy storage systems. Current technology Ni-H batteries have a specific energy of 32 W-hr/kg, with up to 75 W-hr/kg projected. Regenerative hydrogen/oxygen fuel cells planned for the lunar surface will have specific energies ranging from 700 to 1200 W-hr/kg (Personal communication from David J. Bents of NASA Lewis Research Center, Cleveland, OH, 1990).

Some other power levels were investigated and are presented in Table 1. The use of a thermochemical reaction for small power generation, as expected, requires less raw material which is easier to obtain from lunar soil. The major drawback of this concept is the weight, specifically the amount of water needed for the power levels investigated.

TABLE 1. THERMOCHEMICAL SYSTEM MASS

COMPONENT	100 kW	50 kW	25 kW
Solar Concentrator (kg)	981	490	280
Reactors (kg)	695	354	193
Radiators (kg)	433	226	123
Tanks (kg)	997	515	279
Power Management and Distribution (kg)	400	200	100
Heat Exchangers (kg)	17	8	5
H <sub>2</sub> O (kg)	969,348	514,158	281,359

### FEASIBILITY

Aside from theoretical considerations there are some technical barriers which would have to be overcome before the CaO/H<sub>2</sub>O system could compete with batteries and fuel

cells. One problem is a reactor design. There may be problems with the heat transfer within the reactor, but metal fins may overcome the problem. A corrosion reaction with stainless steel has been observed<sup>1</sup> and the effect of corrosion on the lifetime of a reactor made of Inconel is not known. If Inconel is not suitable, then either another alloy could be used, or a protective coating could be deposited inside the reactor. The amount of water needed for the reaction is a critical issue, as this resource is not available on the moon.

The second major technical barrier is the extraction of CaO from the lunar soil. The chemical composition of the lunar soil is listed below:<sup>6</sup>

	<u>Maria (seas)</u>	<u>Terrae (highlands)</u>
SiO <sub>2</sub>	45 %	45.0 %
FeO	20 %	4.0 %
Al <sub>2</sub> O <sub>3</sub>	8 %	28.0 %
CaO	9 %	16.0 %
MgO	14 %	6.0 %
TiO <sub>2</sub>	2 %	.4 %

The CaO content is highest in the highlands, so highland soil should be processed to obtain the CaO. A dry-extraction process has been proposed to recover the "useful" products, silicon, aluminum, and oxygen, from the mineral amorphite (CaAl<sub>2</sub>Si<sub>2</sub>O<sub>8</sub>) in the lunar soil.<sup>15</sup> The "waste" product of the process, CaO, can thus be used productively for energy storage. An HF acid leach process has also been proposed for separation of lunar soil.<sup>16</sup> This process offers total separation into the elements (Al, Ca, Fe, Mg, Si, Ti) or their oxides. It therefore appears that the basic technology for CaO extraction has been established. Because CaO is a by-product of lunar soil separation, the mass of a soil separation system was not included in the specific energy calculation since no extra equipment is needed to be brought from earth.

The CaO/H<sub>2</sub>O reaction is simple: no catalysts or special conditions are necessary. The basic design and technology are also relatively simple. The most significant foreseeable technical difficulty would be processing of the lunar soil, construction in the lunar environment and problems associated with a closed system, such as pressure control and pumping.

#### CONCLUSIONS:

The CaO/H<sub>2</sub>O thermochemical energy storage system has been proposed as a candidate for lunar energy storage. In the processing of lunar soil, CaO was previously considered to be an unwanted by-product, but it has a potential use in energy storage. In addition to providing energy storage for the lunar night, the CaO/H<sub>2</sub>O system also produces electricity during the day: a feature not offered by other storage systems. Another advantage is the fact that the water has numerous other uses (source of H<sub>2</sub> and O<sub>2</sub>, life support, etc.).

The major disadvantages of the CaO/H<sub>2</sub>O system are the complexity of the reactor design and its unknown lifetime, the processing of the lunar soil to obtain CaO, construction in the lunar environment and the required water for the reaction. Because of the need for lunar soil

processing, the CaO/H<sub>2</sub>O system would not be an option for an initial moon settlement. Further investigation is needed for a more accurate calculation of specific energy, evaluation of feasibility, and determination of the lifetime and cost of the system to allow more precise comparison with other systems.

#### Acknowledgements

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#### REFERENCES:

- 1- Rosemary, J.K., Baurle, G.L., and Springer, T.H., "Solar Energy Storage Using Reversible Hydration-Dehydration of CaO-Ca(OH)<sub>2</sub>," *J. Energy*, 3 (6), 1979.
- 2- Fujii, I., and Tsuchiya, "Experimental Study of Thermal Energy Storage by Use of Reversible Chemical Reactions," *Alternative Energy Sources*, Vol. 9, Hemisphere, 1978.
- 3- Werekro-Brobby, Y., and Gibbs, B.M., "Calcium Hydroxide as an Energy Storage Medium for Solar Power Systems," *Inter. Conf. on Future Energy Concepts, Proceedings*, 1979.
- 4- Nix, R.G., Bergeron, P.W., and West, R.E., "Reversible Chemical reactions for Energy Storage in a Large Scale Heat Utility," presented at the 17<sup>th</sup> Intersociety Energy Conversion Engineering Conference (IECEC), 1982.
- 5- Fujii, I., et al, "Studies of an energy Storage System by Use of the Reversible Chemical Reaction: CaO + H<sub>2</sub>O ⇌ Ca(OH)<sub>2</sub>," *Solar Energy* 34 (4), 1985.
- 6- Smith, R. E., and West, G. S., "Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development," Vol. 1, NASA Technical Memorandum 82478, 1982.
- 7- Kanzawa, A., and Arai, Y., "Thermal Energy Storage by the Chemical Reaction: Augmentation of Heat Transfer and Thermal Decomposition in the CaO/Ca(OH)<sub>2</sub> Powder," *Solar Energy* 27 (4), 1981.
- 8- Samms, J.A.C., and Evans, B.E., "Thermal Dissociation of Ca(OH)<sub>2</sub> at Elevated Pressures," *J. Appl. Chem.* 18, Jan. 1968.
- 9- Work, K., "Thermodynamics," McGraw Hill Co., 1983.
- 10- Smith, R.D., "Chemical Energy Storage for Solar Thermal Conversion," Rocket Research Company, Final Report, RRC-80-R-678, April 1979.
- 11- Bauerle, G.L., Pearlman, H., Rosemary, J.K., and Springer, T.H., "Solar Energy Storage by Reversible Chemical Processes," Rockwell International Corp., Final report, Sandia Contract Fao 92-7671, Jan. 1979.
- 12- Schmidt, E. W., and Lowe, P.A., "Thermochemical Energy Storage Systems," *Proceedings 11<sup>th</sup> IECEC* 1976.
- 13- Abhat, A. and Huy, T.Q., "Heat and Mass Transfer Considerations in a Thermochemical Energy Storage System Based on Solid-Gas Reactions," *Solar Energy* 30 (2), 1983.
- 14- Kunii, D., and Levenspiel, O., *Fluidization Engineering*, John Wiley & Sons, New York, p 482-489, 1969

- 15- Keller, R. "Silicon, Aluminum, and Oxygen from Lunar Ore," Space Manufacturing 6: Nonterrestrial Resources, Biosciences, and Space Engineering, Proceedings of the Eighth Princeton/AIAA/SSI Conference, October 1987.
- 16- Waldron, R.D., "Total Separation and Refinement of Lunar Soils by the HF Acid Leach Process," Space Manufacturing 5: Engineering with Lunar Asteroidal Materials, Proceedings of the Seventh Princeton/AIAA/SSI Conference, October 1985.
- 17- Wereko-Brobby, C.Y., and Gibbs, B.M., "Calcium Hydroxide as an Energy Storage Medium for Solar Power Systems," International Conference on Future Energy Concepts, pp 207-210, Jan 30-Feb 1, 1979, London

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