

NASA Technical Memorandum 103145

Energy Storage for a Lunar Base by the
Reversible Chemical Reaction:
 $\text{CaO} + \text{H}_2\text{O} \rightleftharpoons \text{Ca}(\text{OH})_2$

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June 1990

NASA

(NASA-TM-103145) ENERGY STORAGE FOR A LUNAR
BASE BY THE REVERSIBLE CHEMICAL REACTION:
CaO+H2O REVERSIBLE REACTION Ca(OH)2 (NASA)
7 p CSCL 10C

N90-25419

Unclas

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ENERGY STORAGE FOR A LUNAR BASE BY THE REVERSIBLE CHEMICAL REACTION: $\text{CaO} + \text{H}_2\text{O} \rightleftharpoons \text{Ca}(\text{OH})_2$

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Abstract

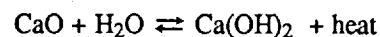
A thermochemical solar energy storage concept involving the reversible reaction $\text{CaO} + \text{H}_2\text{O} \rightleftharpoons \text{Ca}(\text{OH})_2$ is proposed as a power system element for a lunar base. The operation and components of such a system are described. The $\text{CaO}/\text{H}_2\text{O}$ system is capable of generating electric power during both the day and night. The specific energy (energy to mass ratio) of the system was estimated to be 155 W-hr/kg. Mass of the required amount of 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, NiH batteries, flywheels, and superconducting inductors, in addition to beamed power (Personal communication from David J. Bents of NASA Lewis Research Center, Cleveland, OH, 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 (refs. 1 to 5). 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:



The fact that CaO is a major constituent of lunar soil (9 to 16 percent) (ref. 6) singles out this reaction as a possible solar energy storage system for a moon base.

Process Description

In the proposed system, figure 1, direct solar radiation incident on a concentrator is directed onto a reactor (heat receiver). The calcium hydroxide inside the receiver is dissociated at a temperature of 500 to 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 stored at 25 °C. When required, CaO and H_2O are combined, initiating the chemical reaction and the heat of reaction is liberated.

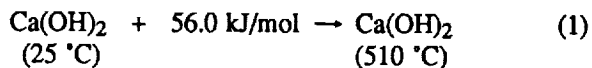
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System Calculation

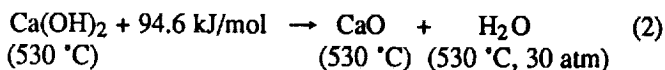
Chemical Reaction

There are two types of energy storage involved in this reaction: sensible heat (heating from 25 to 510 °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 $\text{Ca}(\text{OH})_2$ to the dissociation temperature (510 to 550 °C), producing CaO and steam (which is condensed and stored as liquid water):

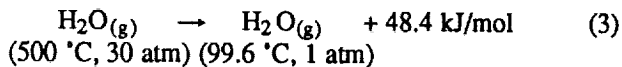
Charging reactions:



The amount of energy needed to heat calcium hydroxide from 25 to 530 °C is 56 kJ/mol (ref. 7), known as the sensible heat.



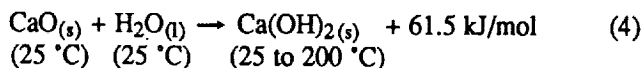
The heat of reaction for the above at a temperature range 530 to 800 °C was calculated by Samms & Evans (ref. 12) and was found to be 94.6 kJ/mol.



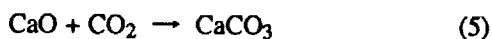
The energy released by reaction (3) is used to generate electrical power by use of a steam turbine (ref. 9).

The water is brought in contact with the CaO , forming $\text{Ca}(\text{OH})_2$ and releasing large amounts of energy, which can be used for a secondary electrical power generation:

Discharging reactions (ref. 13):



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 $\text{CaO}/\text{H}_2\text{O}$ reaction. The major side reaction of concern for $\text{CaO}/\text{H}_2\text{O}$ solar energy storage systems on earth is the reaction of CaO with carbon dioxide:



forming CaCO_3 , which has a higher dissociation temperature (898 °C). On the moon, however, this will not be a problem because of the lack of CO_2 . Another potential side reaction is the formation of noncondensable gases (mainly H_2) if a corrosion reaction with a stainless steel container occurs (ref. 1).

This side reaction does not reduce the reversibility by consuming the reactants, but rather by the presence of the non-condensable gases which reduce the partial pressure of the water vapor. Removing these gases by degassing the apparatus restores the reversibility of the reaction. This would easily be accomplished on the moon by venting the reactor because the moon has negligible atmosphere. Tests have shown that the degree of reaction completion is 94 to 99 percent after over 1100 hydration/dehydration cycles if the formation of CaCO_3 is not taken into account (refs. 1 and 8).

A major concern for $\text{CaO}/\text{H}_2\text{O}$ 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 $\text{Ca}(\text{OH})_2$, which have a low thermal conductivity (refs. 5, 7, 10, and 11). Reaction times were typically about 2 hr 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 (ref. 12). 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.

Energy and Mass Balance

In order to estimate the solar collector area and flow rate required to produce 100 KWe power generation system to operate on the lunar surface, the following was assumed:

- (1) A conversion of stored energy to chemical reaction in the dissociation reactor has an efficiency of 84 percent (ref. 4);
- (2) The solar collector weighs 1.5 kg/m²
- (3) The steam turbine specifications are: 500 °C, 30 bar, turbine efficiency of 80 percent, steam quality of 0.2;

The energy and mass balance based on the above assumptions are presented in figure 3.

Reactor Design

The reactor design recommended for this noncatalytic reaction is a continuous (moving bed) reactor (ref. 13). There is direct heat transfer between the reacting solids and the gas. The shrinking core model and the following assumptions were made in order to estimate the solids residence time and reactor size.

- (1) The rate controlling mechanism is a chemical reaction;
- (2) Residence time is the same for all solid particles;
- (3) The H_2O vapor concentration is constant throughout the reactor;
- (4) Solid particles are uniform in size, 1 mm;

The estimated solids residence time based on the above assumptions is 1.5 min; the reactor size calculations were made using twice this estimated time.

Specific Energy

For the 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 hr; hence 1.26×10^8 kJ of electrical energy is needed, which corresponds to 88 125 kg of H₂O. Adding 10 percent to account for vapor losses during reactor evaluation, reversibility losses, and extra water needed as the working fluid means that about 96 938 kg of H₂O will be needed. Also, 274 478 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 which need to be brought from earth are listed below.

<u>Component</u>	<u>Mass (kg)</u>
Solar concentrator	516
H ₂ O tanks	88
Reactors	44 000
Radiator	34 041
Power management and distribution	200
Pumps	600
Heat exchangers	<u>50 000</u>
Subtotal	129 445
Water	96 938
Total	226 383

The reactor construction material selected was Inconel (density = 8.3 g/cm³).

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 as follows

$$\text{specific energy} = \frac{\text{energy}}{\text{mass}} = \frac{(100 \text{ kW})(350 \text{ hr})}{2.26 \times 10^5 \text{ kg}} = \frac{155 \text{ W-hr}}{\text{kg}}$$

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).

Feasibility

Aside from theoretical considerations there are some technical barriers which would have to be overcome before the CaO/H₂O 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 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 second major technical barrier is the extraction of CaO from the lunar soil. The chemical composition of the lunar soil is listed below (ref. 6):

	<u>Maria (seas),</u> <u>percent</u>	<u>Terrae (highlands),</u> <u>percent</u>
SiO ₂	45	45.0
FeO	20	4.0
Al ₂ O ₃	8	28.0
CaO	9	16.0
MgO	14	6.0
TiO ₂	2	0.4

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 (CaAl₂Si₂O₈) in the lunar soil (ref. 14). The "waste" product of the process, CaO, is actually the useful product in this case. The HF acid leach process has also been proposed for separation of lunar soil (ref. 15). 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/H₂O 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 problems associated with a closed system, such as pressure control and pumping.

Conclusions

The CaO/H₂O thermochemical energy storage system has been proposed as a candidate for lunar energy storage. In the processing of lunar soil, CaO is 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/H₂O system also produces electricity during the day: a feature not offered by other storage systems.

The major disadvantages of the CaO/H₂O system are the complexity of the reactor design and its unknown lifetime and the processing of the lunar soil to obtain CaO. Because of the need for lunar soil processing, the CaO/H₂O 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 before comparison can be made to other systems.

Acknowledgements

The authors would like to thank David J. Bents, Lisa L. Kohout, and Paul Schmitz from the Power Systems Integration Office at the NASA Lewis Research Center for their valuable advice and guidance.

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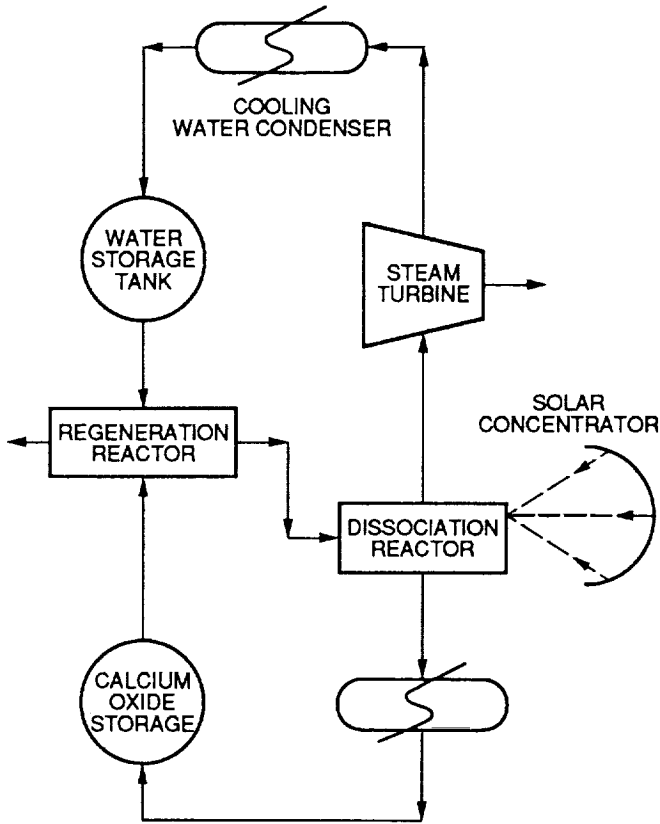


Figure 1. - Solar power generation system with calcium hydroxide as storage medium.

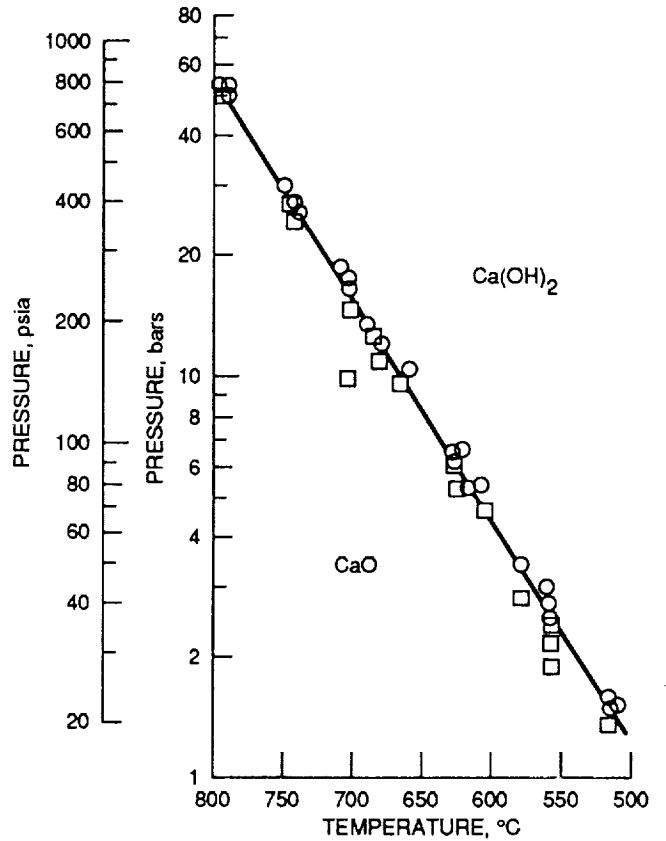


Figure 2. - Pressure versus dissociation temperature for $\text{CaO} + \text{H}_2\text{O} \rightleftharpoons \text{Ca(OH)}_2$ (ref. 12).

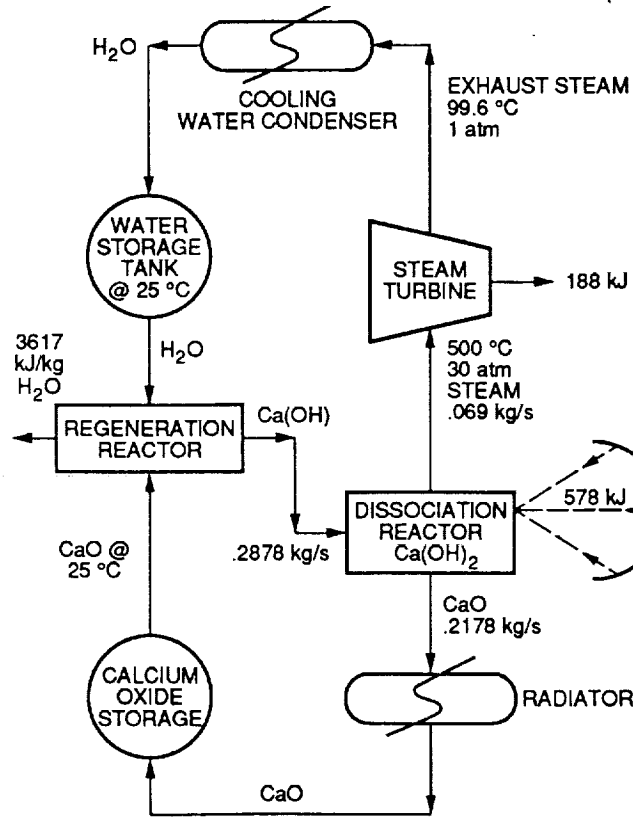


Figure 3. - Energy and mass balances.



National Aeronautics and
Space Administration

Report Documentation Page

1. Report No. NASA TM-103145		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Energy Storage for a Lunar Base by the Reversible Chemical Reaction: $\text{CaO} + \text{H}_2\text{O} \rightleftharpoons \text{Ca}(\text{OH})_2$				5. Report Date June 1990	
				6. Performing Organization Code	
7. Author(s) Marla E. Perez-Davis and Frank DiFilipo				8. Performing Organization Report No. E-5497	
				10. Work Unit No. 506-41-41	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001				14. Sponsoring Agency Code	
15. Supplementary Notes Marla E. Perez-Davis, NASA Lewis Research Center; Frank DiFilipo, Case Western Reserve University, Cleveland, Ohio 44106 and Summer Intern at NASA Lewis Research Center.					
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17. Key Words (Suggested by Author(s)) Energy storage; Thermochemical; Lunar base; Lunar night; Calcium oxide			18. Distribution Statement Unclassified - Unlimited Subject Category 44		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 6	22. Price* A02