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HYDROGEN RESOURCES FOR THE MOON; Richard J. Williams, Code SL, NASA Headquarters, Washington, D. C. 20546.

If abundant supplies of hydrogen and oxygen are available on the moon, a viable economy based on the reaction of hydrogen and oxygen to produce water can be constructed. The uses of hydrogen, oxygen, and water are manifold: Biological, power production, and propulsive systems can all effectively function on this hydrogen economy. If the use of such an economy is proposed, then largely independent of any other assumptions, the magnitude of the hydrogen and oxygen resource needs is the same as the stoichiometric ratio of hydrogen to oxygen in water--that is, 0.125 by weight.

Oxygen, combined as oxides and silicates, is relatively abundant on the moon, comprising in excess of 50% by weight of lunar materials (1). The average lunar hydrogen resources are the order of 0.01% by weight; no significant indigenous water is present in the returned lunar materials. The ratio of hydrogen to oxygen is 0.0002 on the moon, and consequently effective exploitation of lunar oxygen resources will require the importation of hydrogen to the moon. The basis of such an economy is a series of chemical reactions, and any analysis of the economics of importation should be normalized to moles of material. If mass delivery is the primary cost driver for importation, then hydrogen which has the greatest number of moles per unit mass of all the elements would be the most economical material to import. Because of the extremely small quantities of indigenous lunar hydrogen and the large quantities of hydrogen necessary to match the lunar oxygen resources, it is doubtful if an economy independent of imported hydrogen can ever evolve.

The lunar hydrogen economy can be summarized as the following two steps:

1. Hydrogen is reacted with lunar material to produce water via reactions like--$H_2 + MO = M + H_2O$ (in which M represents a metal or metals);

2. The resultant water is used for biological purposes and, in part, decomposed to free hydrogen and oxygen for biological and other uses.

In theory such a system can be closed so that once a stable steady state is attained, nothing but energy need be added to keep the system cycling. In practice, however, unintentional losses--leaks--and intentional losses--fuels for propulsion and other exports--will occur. The system is open; and, in addition to energy, lunar soil and hydrogen must be continually added to maintain a viable system. Both the energy and resource requirements of the open system will be larger than the equivalent closed system; the net economics of such a system can only be judged in the context of the larger system of which it is a part.

A metals industry can be formed on the basis of the reaction given in step 1 above. The process would be a form of zone refining based on the relative reducibility of the various materials. The general reaction given involves gases--hydrogen and water--on opposite sides of the reaction, and thus it can always be made to proceed to the right to some extent by adjusting the ratio of hydrogen to water--that is, the rate at which hydrogen is admitted to the process relative to the rate at which water is withdrawn from it. Thus, a desirable adjunct to a lunar hydrogen economy would be a substantial metals industry. Eventually a net export of metals should be attained. This export might form the base for an economically self-sufficient lunar colony.

The production processes would also produce by-products. Some, such as carbon (10-80 ppm), nitrogen (40-120 ppm), and helium (5-25 ppm), are useful and not harmful; others, such as sulfur (500-22,000 ppm), are potentially useful, but also harmful. As examples, carbon could be used in steel production; nitrogen, after conversion to ammonia, as fertilizer; and helium, as a dilutant for oxygen in the breathing atmosphere. Sulfur would probably be released from the process as hydrogen sulfide and would be highly injurious to plants and animals and damaging to many aspects of the physical system of a colony, for example, fuel cell membranes. Any system design must account for these by-products by putting them to desirable uses and neutralizing their undesirable effects.

Some of these physical resources, products, and by-products are systematized in the table below:

Minimum Biological Needs (per man per day at 100% chemical efficiency)(2)

Resources (grams) -

Hydrogen	250
Lunar Mare Material	4320

Products (grams) -

Water	2160

By-Products (grams) -

Iron	230-500
Sulfur	2-95
Nitrogen	0.17-0.52
Carbon	0.04-0.35
Helium	0.02-0.11

These quantities do not appear to be disturbingly large until the process is scaled to colonies of 10,000 people and the needs expanded to more than just the biologically necessary minimum. On such scales, sulfur accumulations in excess of a metric ton per day would occur while at least 100 kilograms of helium would be freed per day.

In summary, a hydrogen economy based on the use of lunar materials and imported hydrogen would be useful in space colonization. Such an economy includes a large metals industry as a natural adjunct. It may be possible for such colonies to become economically self-sufficient by exporting metals. Many other by-products would result from the reaction of lunar material with hydrogen to produce water. Some of these have properties which make them useful; others have undesirable properties and could pollute the system. Although the present discussion has been directed toward a lunar colony, most of the comments would be relevant to the exploitation of asteroidal resources or of those other satellites. Planning of a colony based on a hydrogen economy should incorporate the facts that at least hydrogen will have to be imported and that the by-products of the processes are not minor, useless, or harmless.

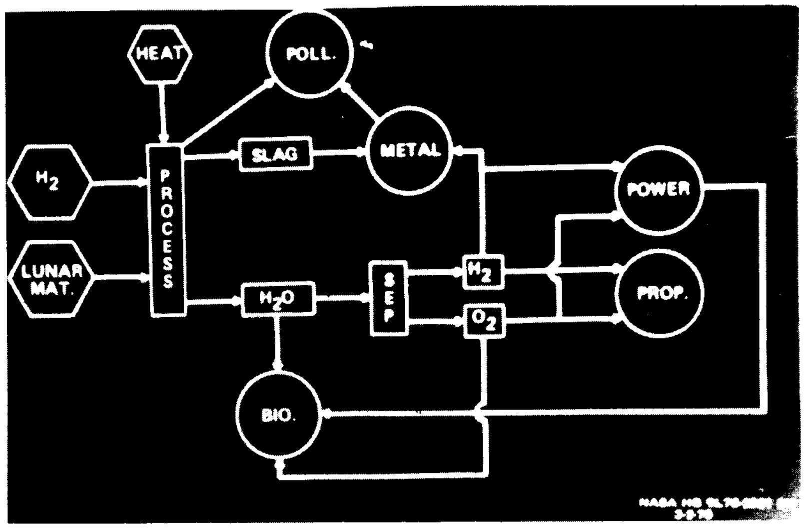
NOTES

1. This and other abundance data have been retrieved from various papers in the Proceedings of the Lunar Science Conferences, 1 through 6. They refer to mare basalt chemistries and in many cases have been converted from original data into the units used in this paper. A basic, but not as complete, reference would be S. R. Taylor (1975) Lunar Science: A Post-Apollo View, Pergamon Press, Inc., New York, 372 pp.

2. Many investigators have studied the resource and technology needs for a lunar colony. Those in Design of a Lunar Colony, 1972 NASA/ASEE Systems Design Inst., Rept. on NASA Grant NGT 44-005-114 summarize much of the earlier work and have been used as the basis of the ideas present in this study.

HYDROGEN RESOURCES FOR THE MOON

Richard J. Williams



A flow chart for hydrogen in a lunar economy. The biological (BIO.), pollution (POLL.), and propulsion (PROP.) aspects of the system have not been analyzed and are considered only as resource sinks.

DISCUSSION (Williams Paper)

SPEAKER 1: To dilute your oxygen for breathing purposes, I will propose that the helium might be more abundant and equally useful component.

WILLIAMS: It might well be. That is indeed another of the socalled byproducts that I neglected in the analysis. But, yes, that would be a very effective medium.

SPEAKER 2: You mentioned the availability of nitrogen. Could you give us some idea of what the fraction of nitrogen might be?

WILLIAMS: It's approximately 100 ppm. You have a fairly abundant supply of it.

SPEAKER 3: I want to point out again that nitrogen is highly enriched in the fine-grain materials, so there's an advantage there in concentrating that material.

WILLIAMS: Yes, this whole aspect to the concentration to the fine-grain material is something that has to be looked at carefully. It depends on what levels of concentration you really do get when you take the effort to concentrate it, which requires the input of energy and work to do it ; where that balancing out occurs determines whether you really can use the finest fractions to get all the resources you need. I have not seen that analyzed in a straightforward, complete manner, where I can say, yes, it is worthwhile to do that in terms of the net functioning of your economy.

SPEAKER 4: It wasn't clear to me, but was your last calculation of your energy requirements to support a human being based on the binding energy of the water molecule which he drinks during a year?

WILLIAMS: No. It was based on the fact that your economy has to run basically on the separation of hydrogen. I may have mentioned drinking but I meant the breathing, the supply of oxygen due to that decomposition.

SPEAKER 4: Why do you have to decompose the water molecule to supply the human body with water?

WILLIAMS: No, to supply him with oxygen. To breathe.

SPEAKER 5: Surely you're considering the possibility of supplying the oxygen biologically. If you have to raise food, why aren't you thinking about a photosynthetic plant?

DISCUSSION (Williams Paper)

WILLIAMS: You can close your cycle that way, but at low efficiencies.

SPEAKER 5: That is, of course, the same solar energy that you might use with solar cells or other things, but it's pretty readily available.

WILLIAMS: Right. But I think, again, the point is that, no matter how you do it, you've got to pump energy into the system and it's got to be a lot of energy and it is of the order of that decomposition reaction for water for scaling purposes.

SPEAKER 6: For an importation of oxygen and hydrogen simultaneously, I feel that the hydrogen peroxide is a good material to transport because itself is unstable already at the higher energy level, so it takes less energy to take apart the hydrogen and oxygen; thus you save a lot of energy need.

WILLIAMS: Well, I think initially, what you find is that the driver is the amount of material, in my terms the amount of moles of material that you supply to the system per unit weight going up. I'd much prefer to import hydrogen because I get more moles per gram of that than anything else. I think the economics of transporting things work out that way fairly well.