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Production of Oxygen on the Moon: Which Processes Are Best and Why

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Although over 20 processes have been put forth for the liberation of oxygen from lunar materials, many are largely untested and/or extremely complicated and difficult to implement. Simplicity, low energy, easily attainable feedstock, and resupply mass are the keywords for the processes that will ultimately be selected for the initial production of oxygen on the moon. An evaluation of the 20 processes has resulted in a ranking according to overall feasibility. At this time, the eight processes considered to be the most likely candidates for oxygen production on the moon are vapor pyrolysis; glass reduction with H_2; molten silicate electrolysis; ilmenite reduction with H_2, CO, and CH_4; fluxed molten silicate electrolysis; and ion plasma pyrolysis. However, it is too early in the development of all of these processes to eliminate any from consideration.

Introduction

ESTIMATES of the costs of transporting materials from Earth to the moon range from $20,000 to $30,000 per pound. Therefore, it is imperative that we learn to utilize the resources on the moon to partially offset these astronomical expenses. Along these lines, the production of oxygen on the moon utilizing indigenous materials is crucial to the establishment and development of an autonomous lunar colony. The need for oxygen for sustaining human existence is paramount. But this lunar liquid (LLOX) could result in tremendous cost savings on fuel for effective transportation systems, particularly with its export to low-Earth orbit.

In anticipation of a return to the moon, it will be necessary to conduct extensive engineering/science studies of uses of lunar materials. The wealth of engineering experience in industry, government, and academia must be integrated to develop concepts and designs for effective resource utilization. The most complete compilation of various engineering aspects of LLOX productions was prepared by Christiansen et al.[1] Other sources that have been used extensively are those of Taylor,[2,3] Taylor and Carrier,[4-6] and Taylor and McKay.[7]

There are over 20 different process concepts that have been proposed for the production of oxygen from lunar materials. A compilation of these processes is given in Table 1. They are in various stages of development, ranging all the way from early engineering concepts to proven schemes. An evaluation of these processes,[5,6] which bears on their feasibilities for winning oxygen from lunar materials, has resulted in their ranking. Eight of the most promising processes have been selected for brief discussion, and the concepts and principles of these are presented later. The several factors involved in the ranking of the 20 processes, albeit highly subjective, are discussed. This ranking is only a paradigm based on a first approximation of their potentials for success. Perhaps the major conclusion of this review is that considerably more research and experimentation is needed before any really definitive evaluation of these processes is possible. Some of these requisite studies are in progress.

Processes Involving Solid/Gas Interaction

It is possible to react various lunar minerals and glasses with a variety of gases to produce oxygen. Figure 1 is a schematic depicting the various steps in a solid/gas reaction for the production of LLOX. The gas can be H_2, CO, or CH_4. Although the solids can be any of several, most of these processes involve the mineral ilmenite, $FeTiO_3$. Basically, the reduction of ilmenite can be considered as the reduction of the FeO portion of the ilmenite, with the release of oxygen, leaving a product of TiO_2 and Fe^0. These are not necessarily new processes. However, the products sought in the past were metals, and the oxygen was discarded. For lunar application, it is the liberated oxygen that is of greatest value, with the metals being possible byproducts.

Ilmenite Reduction with H_2, C/CO, or CH_4

Ilmenite, $FeTiO_3$, makes up 10–20% by volume of some mare basalt rocks and lesser amounts of mare solids. An ilmenite feedstock can be produced by beneficiation of high-Ti mare basalt soils[7,8] and rocks.[9] The kinetics of ilmenite reduction are considerably faster than those for silicate minerals.[10-12]

The hydrogen-reduction process has been studied extensively by Gibson and Knudsen.[13,14] In fact, Carbotek, Inc. (Houston, TX), has patented an ilmenite hydrogen-reduction technique involving a three-stage fluidized-bed process for the production of LLOX (Fig. 2).[15] Zhao and Shadman[16] have recently investigated the carbon monoxide reduction process. This overall process can have essentially the basic fluidized-

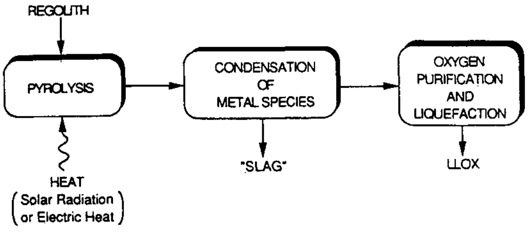

Fig. 1 Flow diagram of solid/gas reduction processes for the production of LLOX.

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Table 1 Potential processes for oxygen production on the moon

- Solid/gas interaction
  - Ilmenite reduction with hydrogen
  - Ilmenite reduction with C/CO
  - Ilmenite reduction with methane
  - Glass reduction with hydrogen
  - Reduction with hydrogen sulfide
  - Extraction with fluorine
  - Carbochlorination
  - Chlorine plasma reduction
- Pyrolysis
  - Vapor pyrolysis
  - Ion plasma pyrolysis
  - Plasma reduction of ilmenite
- Silicate/oxide melt
  - Molten silicate electrolysis
  - Fluxed molten silicate electrolysis
  - Caustic dissolution and electrolysis
  - Carbothermal reduction
  - Magma partial oxidation
  - Li or Na reduction of ilmenite
- Aqueous solutions
  - HF acid dissolution
  - H_2SO_4 acid dissolution
- Coproduct recovery
  - Hydrogen-helium-water from soil

bed design put forth for hydrogen (Fig. 3). In fact, this also holds for the methane-reduction process, which has been studied by Friedlander.[17]

The reduction of solid ilmenite by H_2, CO, and CH_4 involves the following chemical reactions, respectively:

$$FeTiO_3 + H_2 = Fe + TiO_2 + H_2O$$

$$FeTiO_3 + CO = Fe + TiO_2 + CO_2$$

$$FeTiO_3 + CH_4 = Fe + TiO_2 + CO + 2\ H_2$$

$$2\ CO + 6\ H_2 = 2\ CH_4 + 2\ H_2O$$

The products of water and carbon dioxide can be electrolyzed into $H_2 + O_2$ and $CO + O_2$, respectively, with the collection of the LLOX and the recycling of the reactant gases. It is proposed that the three-stage fluidized-bed reactor should be equally applicable to all of these processes.

Glass Reduction with Hydrogen

Lunar glass, particularly from mare regions, can contain FeO contents up to 20 wt %. McKay et al.[18] and Allen et al.[19] demonstrated that this FeO component of the glass can be readily reduced by hydrogen to yield elemental Fe^0 (native Fe) and water. Thermodynamically, the glass is considerably more unstable than the silicate minerals from which it formed; hence, the rapid kinetics of reduction. The water so produced can be easily hydrolyzed or otherwise electrolyzed to yield oxygen and recyclable hydrogen:

$$FeO_{(glass)} + H_2 = Fe^0 + H_2O$$

$$H_2O = H_2 + ½\ O_2$$

Glass is an abundant constituent of the lunar regolith,[3] mostly as the result of melting produced by meteorite and micrometeorite impacts but also from volcanic activity (e.g., the orange soil at Apollo 17). The impact glass usually welds together rock and mineral fragments into aggregates called agglutinates that frequently constitute over 50 vol % of a given mature soil. In addition, there are entire regions of the moon that have blankets (1-4 m deep) of volcanic glass as pyroclastic deposits. These are termed dark mantle deposits.

Although this scheme for oxygen production is a relatively recent development, it is not too soon to consider its feasibility. It may be possible to utilize a fluidized-bed reaction vessel, similar to that proposed for the reduction of ilmenite with hydrogen (Fig. 2). Considerations of the possible feedstocks would depend on the actual engineering of the process. It would be easiest to use a pyroclastic soil because it consists almost entirely of volcanic glass with a narrow range of grain sizes (e.g., 40-100 μ); an example is the orange soil, Apollo 17 sample 74220, from Shorty Crater. This would require no beneficiation; however, it is more likely that a mare soil will be utilized, at least for the first lunar base.

The agglutinitic glass of typical high-Ti mare soil can be readily beneficiated by magnetic separation, as has been demonstrated by Taylor and Oder.[8] However, because glass sinters at much lower temperatures than the silicate minerals, it may be better to use unbeneficiated mare soil because the silicate mineral and rock fragments might hinder sintering of the glass particles, which could be a significant problem. An additional possible benefit from the use of largely unbeneficiated soil may be realized if the plant is actually located in a high-TiO_2 mare. The feedstock would undoubtedly contain ilmenite, which has reduction kinetics even faster than those for glass. This oxide mineral also would undergo reduction and release its oxygen, thereby adding to the recovery/unit mass of feedstock. Such a scenario would permit the use of soil that has undergone no beneficiation, albeit only a rough screening.

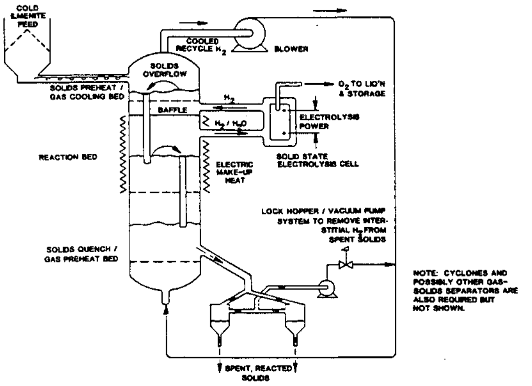

Fig. 2 Hydrogen reduction of ilmenite by a three-stage fluidized-bed process, as modified after Gibson and Knudsen.[13]

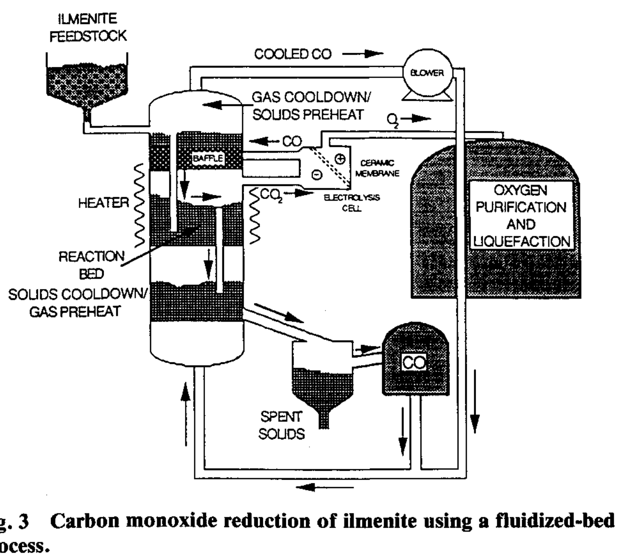

Fig. 3 Carbon monoxide reduction of ilmenite using a fluidized-bed process.

Processes Involving Silicate/Oxide Melt

The concept of electrolysis entails immersing two electrodes in a vat of molten silicate liquid (geologically termed a magma) and imposing a current between the electrodes, as schematically shown in Fig. 4. Oxygen is derived at the anode and metal (mostly Fe and Si) at the cathode. In contrast to many other processes, oxygen is liberated directly at the anode, with no need for further refinement. This is in contrast to hydrogen reduction of ilmenite, for example, which produces water requiring electrolysis. In addition, this is a non-site-specific process; i.e., the feedstock can be almost any lunar resource, highlands or mare.

Molten Silicate Electrolysis

Derivation of oxygen by molten silicate electrolysis has been amply demonstrated experimentally in melts with a variety of compositions.[20-23] Effects of compositional parameters on the energy requirements are complex but are known to a first approximation.[22] An example of a cell design using this molten silicate process is given in Fig. 5.

Fluxed Molten Silicate Electrolysis

Some of the difficulties of high-temperature corrosion, inherent to the molten silicate processes, can be alleviated by employment of a fluoride flux to dissolve the silicate feedstock. Operating temperatures are decreased, and electrolyte conductance is increased. This use of a flux, initially investigated by Keller[24] and Anthony et al.,[25] has recently been modified by Keller and Taberaux.[26] They proposed the addition of lunar soil to LiF-CaF_2 electrolyte at about 1000°C. However, the resupply mass for flux loss may be significant. This process can probably utilize the same design as depicted in Fig. 5.

Processes Involving Pyrolysis

Pyrolysis is the application of heat to induce chemical change, usually a partial dissociation of the metal oxides associated with vaporization. The metal species are condensed quickly before they can recombine with the oxygen, and the oxygen is left in the vapor to be subsequently condensed and liquefied, as depicted schematically in Fig. 6. High temperatures are necessary, in the range of 2000–10,000°C. Such temperatures can be generated in a plasma torch, microwave plasma, electron beam, solar furnace, or relative systems. Pyrolysis processes can be made virtually independent of Earth-supplied reagents.

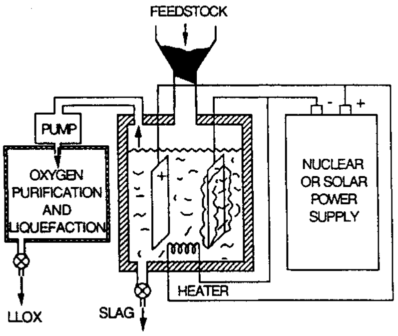

Fig. 4 Schematic diagram depicting the electrolysis of molten silicates to recover LLOX.

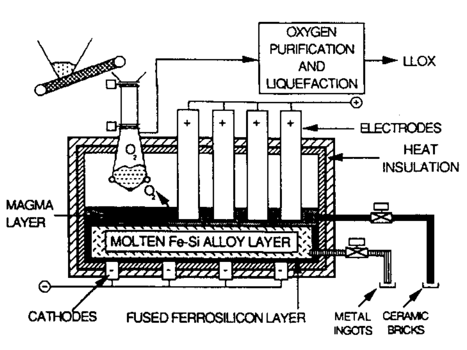

Fig. 5 Molten silicate electrolysis cell for the production of LLOX, as modified after McCullough and Mariz.[21]

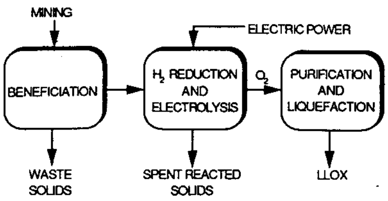

Fig. 6 Schematic diagram depicting the pyrolysis process.

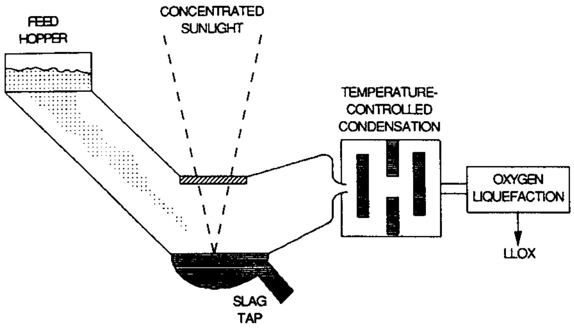

Fig. 7 Vapor-phase pyrolysis cell for the production of LLOX, as modified after the notes of Senior.[29]

Vapor Reduction

Temperatures from 1800 to 3000°C are utilized to vaporize the feedstock and transform oxygen-bearing compounds into monoxides and oxygen.[27,28] After vaporization, the gas is rapidly cooled, and everything except the oxygen is condensed back into liquid or solid. Such a system is shown in Fig. 7. Senior[28,29] has demonstrated the feasibility of the pyrolysis portion of this process using a solar furnace. The direct use of solar energy is a key benefit to this process.

Ion Plasma Separation

Steurer and Nerad[27] reported that, at temperatures of 7000–10,000°C, oxide dissociation products are ionized. At 7700°C, over 90% of the metallic dissociation products (Fe, Ti, Al, Mg) and 25% of the Si are ionized; however, only 1% of the oxygen is ionized. The ionized metals can be extracted from the vapor by electrostatic/electromagnetic means, whereas neutral oxygen flows downstream for collection. At first glance, it would seem that this process might be energy intensive. However, because of the low amount of "process throughput," the actual energy requirements should be relatively low (Table 2).

Consideration of the Process Concepts

Thorough systems definitions of all aspects of oxygen generation processes are necessary. Energy requirements are obviously of great importance, as is consideration of solar vs nuclear-electric power sources. The overall "simplicity" of the process also is paramount. This includes not only the number, complexity, and efficiency of steps in the entire process but also feedstock requirements and costs of "importing" consumable reactants. The sensitivity of process mass and power to both feedstock and production rate is another first-order consideration.

Feedstock

In the evaluation of the lunar feedstock, it must be determined whether sites in maria or highlands are to be occupied and whether rocks or soils are to be mined. Taylor and McKay[7] have presented a discussion of some of the concepts and difficulties to be considered in evaluating raw materials to be beneficiated to produce a given feedstock. They make the point that the nature of the lunar resources and the feedstock that can be feasibly produced must be factored into the engineering design for the oxygen production processes.

Quantity of Lunar Ore

Christiansen et al.[1] concluded that a production rate of 1000 tonne/yr of lunar oxygen would make a significant impact on space transportation. Estimates of the quantities of ore required to produce this much oxygen with each of the eight candidate processes is presented in Table 2. Note that the process throughput is very important because this quantity strongly affects the percent recovery of reagents that is actually achievable; i.e., the greater the throughput, the lower the actual percent recovery.

Plant Mass

The estimated plant mass required to produce 100 tonne/yr of lunar oxygen is also shown in Table 2. For the processes involved with gaseous reduction of either ilmenite or glass, estimated plant sizes fall in the 200 tonne range, primarily due to the large throughputs. On the other hand, the other processes listed in Table 2 have relatively small throughputs that will not require such massive plants.

Energy

The estimated energy required to produce 1000 tonne/yr of oxygen, including obtaining feedstock, is also shown in Table 2. The energy requirements for different processes fall in the 2-4 MW/yr range.

Resupply Mass for Reagent Makeup

In any chemical/physical process involving recycling of reagents, there are always unavoidable losses. In lunar applications, minimizing makeup requirements will be even more important because the transportation costs dwarf the material costs. For example, in the ilmenite reduction with hydrogen process, some hydrogen probably will be lost. However, the lunar soil contains 50-100 ppm by weight of hydrogen, the result of solar-wind implantation.[30] In fact, lunar soil ilmenite contains 500-1000 ppm (0.05-0.1 wt %) hydrogen, a result of its ability to effectively act as a sink for solar-wind particles.[5] Similarly for carbon, lunar soil contains solar-wind carbon in quantities of 5-100 ppm.[31] In the case of ilmenite reduction with H_2, CO, or CH_4, as well as reduction of glass with H_2, it is likely that large portions of the resupply masses for reagent makeups of the gaseous reactants can come from trace components in the feedstocks.

If a continuous process for the molten silicate electrolysis process can be demonstrated to be practical, then the only consumables may be the anodes and cathodes. In addition, although recent experimentation on the use of NaF and LiF for the fluxed molten silicate electrolysis process has produced some promising results, no evaluation of reagent consumption has been made to date. However, there will undoubtedly be some loss of flux, and this will require costly resupply from Earth, a definite negating factor. The vapor pyrolysis and ion plasma pyrolysis processes have yet to be completely defined. Indeed, if these processes rely solely on space resources, the potential for low resupply masses is probable, perhaps only reflecting normal attrition.

Ranking of Processes

An evaluation and semiquantitative comparison has been performed of the 20 proposed processes for oxygen production on the moon. As shown in Table 3, the factors (column headings) that were considered are technology readiness, number of major steps, process conditions, and feedstock requirements. These are some of the factors that were discussed in the more thorough analysis by Taylor and Carrier.[5] It must be thoroughly appreciated that there is considerable subjectivity in these rankings. Even the four different factors themselves are not really of identical importance; however, here we give each points from 1 to 10 and sum the four factors. Much of the data used to compile Table 3 is weak, some approaching guesswork, some recent and reliable, others older and subjective. This table is intended only for preliminary evaluation and comparison.

Technology readiness refers to the perceived evaluation of how much additional work is needed to bring the process to full-scale production. *Number of steps* refers to the complexity of the overall process, realizing that "simplicity" is the guide. Thus, a continuous, effectively one-step process that yields oxygen directly (e.g., molten silicate electrolysis) receives good marks. Also, the perceived ability of the process to be made autonomous and continuous (high priority) vs attended and batch mode is incorporated under this factor. *Process conditions* not only refer to the temperature and energy of the process but also include plant mass. Considerations of "corrosion" entail not only "wear and tear" but also the dangers of handling, such as with HF. *Feedstock requirements* include the factors of 1) site of the ore, i.e., mare versus highlands, 2) quantity of raw ore required for production of 1000 tonnes of oxygen (Table 2), and 3) degree and difficulty of ore processing and beneficiation (throughput of Table 2).

Table 2 Mine and plant characteristics: 1000 tonnes of oxygen/yr

	Ore, tonnes/yr			
Processes	Raw	Process throughput	Plant mass, tonnes	Energy, MW/yr
Ilmenite: high-Ti mare				
Reduction with hydrogen	210,000[a]	21,000[b]	200	3
Reduction with CO	210,000[a]	21,000[b]	225	3.5
Reduction with methane	210,000[a]	21,000[b]	225	3.5
Mare or highlands				
Glass reduction with H_2	160,000[c]	80,000[d]	200	4
Molten silicate electrolysis	5,000[e]	5,000[f]	70	3
Fluxed molten silicate electrolysis	5,000[e]	5,000[f]	80	3.5
Vapor pyrolysis	5,000[e]	5,000[f]	40	2
Ion plasma pyrolysis	5,000[e]	5,000[f]	40	2.5

[a] Assumes feedstock with 50 wt % ilmenite from an ore with 5% available ilmenite for a beneficiation factor of 10.
[b] Assumes approximately 90% conversion of ilmenite.
[c] Assumes soil with 25% glass beneficiated to 50% glass for a beneficiation factor of 2.
[d] Assumes 15% FeO in glass and 75% conversion of FeO to $Fe^0 + O_2$.
[e] No beneficiation necessary.
[f] Assumes about 43 wt % O_2 in soil with 50% recovery.

Table 3 Qualitative comparison of lunar oxygen processes

Processes	Technology[a]	No. of steps[b]	Process conditions[c]	Feedstock[d]	Total	Rank
Solid/gas interaction						
Ilmenite reduction with H_2	8	9	7	3	27	4
Ilmenite reduction with C/CO	7	8	7	3	25	7
Ilmenite reduction with CH_4	7	8	7	3	25	8
Glass reduction with H_2	7	9	7	6	29	2
Reduction with H_2S	2	6	6	8	22	12
Extraction with F_2	5	1	2	10	18	16
Carbochlorination	3	3	3	10	19	15
Cl_2 plasma reduction	4	5	5	10	24	9
Silicate/oxide melt						
Molten silicate electrolysis	6	8	5	10	29	3
Fluxed silicate electrolysis	6	6	5	10	27	5
Caustic dis. electrolysis	5	4	3	10	22	13
Carbothermal reduction	6	3	3	10	22	14
Magma partial oxidation	2	2	4	5	13	19
Li or Na reduction of ilmenite	2	3	5	2	12	20
Pyrolysis						
Vapor pyrolysis	6	8	6	10	30	1
Ion plasma pyrolysis	4	8	4	10	26	6
Plasma reduction ilmenite	7	8	6	3	24	10
Aqueous solution						
HF acid dissolution	5	1	2	10	18	17
H_2SO_4 acid dissolution	5	3	3	5	16	18
Coproduct recovery						
H_2-He-water production	7	9	7	1	24	11

[a] Technology readiness: 1 = major technologic development required; 10 = no major unknowns.

[b] No. of steps: 1 = many (>5); 10 = one step.

[c] Process conditions (temperature, energy, plant mass, corrosion): 1 = severe; 10 = low.

[d] Feedstock requirements: 1 = huge quantities; 2 = mare, beneficiated (ilmenite); 5 = mare unbeneficiated; 10 = any feedstock, unbeneficiated.

Based on this crude evaluation scheme, eight candidate processes are considered to be more feasible than the others for the production of oxygen on the Moon. Suffice it to say, this is considered to be only a "strawman" listing of these processes. Considerably more concept design, experimentation, and systems analysis need to be conducted on all of these processes.

Conclusion

Considerations of various engineering aspects of some 20 processes for the production of oxygen on the Moon have been presented and discussed. This has permitted an evaluation, albeit a preliminary one, of these processes and has resulted in eight likely candidates. Ranked in order, with the highest being first, these are vapor pyrolysis; glass reduction with H_2; molten silicate electrolysis; ilmenite reduction with H_2; fluxed molten silicate electrolysis; ion plasma pyrolysis; ilmenite reduction with C/CO; and ilmenite reduction with CH_4. It must be emphasized that at this time it is too early in the development of any of the 20 processes for oxygen production to completely eliminate any process from consideration.

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