

A CARBOTHERMAL SCHEME FOR LUNAR OXYGEN PRODUCTION

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Carbothermal reduction may be the process of choice for winning oxygen from lunar materials. A wealth of terrestrial engineering experience can be applied to development of a lunar plant. Coproducts, such as slag and steel, can be utilized in lunar operations and may be useful lunar exports. Carbon is a more efficient reductant on a per mass basis than is hydrogen in the competing ilmenite reduction process. An accurate plant design awaits further research to address uncertainties in process kinetics, behavior, catalysts, and reactor materials.

INTRODUCTION

The most useful material to produce on the Moon is oxygen for propellant (Cole and Segal, 1964). During the Apollo flights, about 75% of the Saturn V's effort placed propellant in lunar orbit and on the lunar surface to enable return to Earth. A lunar source of oxygen could double or triple the net lunar base mass (and capability) for a given Earth to LEO mass throughput. It also can provide inexpensive gas for a number of uses in lunar exploration. Lunar oxygen may even be exported to LEO at costs arguably below Earth to LEO launch costs (Salkeld, 1966; Davis, 1983; Andrews and Snow, 1981; Cutler, 1984; Cutler and Hughes, 1985; Simon, 1985).

Transportation requirements and transportation economics for the utilization of lunar resources in Earth orbit are reasonably well understood (although market models are somewhat ill-defined). However, the actual production of basic commodities from available lunar minerals is poorly understood (Duke and Arnold, 1977; McKay and Nozette, 1985). The lunar environment is sufficiently different from the terrestrial environment that plant design and process chemistry will differ substantially from that used on Earth. Currently no accurate plant designs exist that can be used in systems studies or mission definition.

A candidate approach for winning oxygen from lunar minerals is the carbothermal process (Fig. 1), which yields steel as a necessary by-product. The process combines chemistry from steel-making and from coal synthesis gas reforming with electrolysis or thermolysis of water. Research was carried out on the carbothermal reduction process in the early 1960s and was reported in the technical literature and NASA technical reports (Rosenberg *et al.*, 1963a,b; Rosenberg *et al.*, 1964a,b,c,d,e; Rosenberg *et al.*, 1965a,b,c,d,e,f).

560 / Oxygen: Prelude to Lunar Industrialization

Every step in this process has been used extensively in engineering practice. The terrestrial data provide an excellent framework for research on and possible development of this process for the extraterrestrial environment.

The near-term benefits of lunar oxygen are recognized. Lunar steel may also be a near-term useful product. It could be utilized in many lunar base components such as roadbeds, landing pads, instrument foundations, walkways, stairways, pressure vessels, pipes, drill rigs, and cables. A source of lunar steel combined with lunar base propellant production could enable various large scale space projects. If we continue to transport all needed materials from Earth, space activities in the 21st Century will be as they are now—limited and expensive. We must learn to use space resources if we are to change our presence in space from tentative peeks to vigorous exploration and exploitation. The carbothermal processing plant is a good example of a technology that takes maximum advantage of terrestrially derived engineering knowledge to start using extraterrestrial resources.

PROCESS CONSIDERATIONS

The carbothermal process for producing lunar oxygen (Fig. 1) starts with mining regolith and separating out a desirable mineral fraction, probably ilmenite. About 100,000 tons of lunar regolith must be mined per year to produce 1000 tons of oxygen, based on a 10% usable ilmenite content. This corresponds to digging a pit 100-m × 100-m

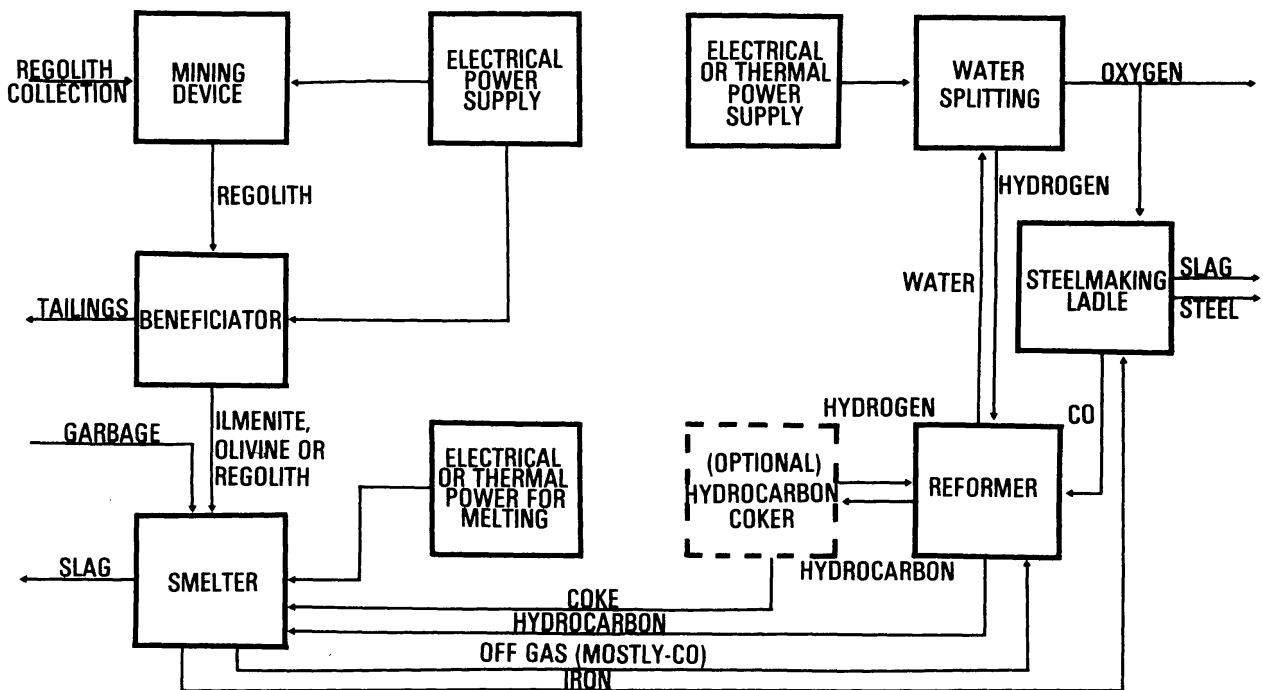
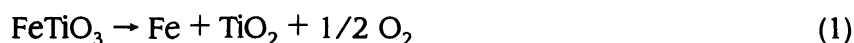


Figure 1. Flow diagram of the carbothermal oxygen production plant. Regolith is mined; steel and oxygen are produced; and tailings, iron-making slag, and steel-making slag are discarded.

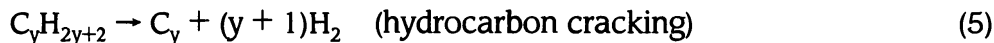
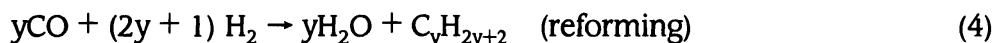
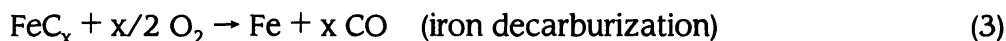
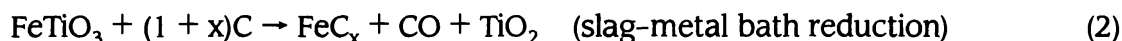
× 5-m deep over the year, about the amount of material excavated in building 1.5 miles of interstate highway. A beneficiator removes oversize material and separates the remainder into tailings and feed material, about 90% ilmenite combined with 10% flux. The tailings are disposed of down a conveniently located slope, and the feed materials charged to the smelter.

In the proposed lunar system, the feed contains ilmenite, anorthite as a fluxing agent, and any carbon-bearing solids garnered from garbage or the off-gas stream. Phase diagrams of the system, $\text{TiO}_2 - \text{SiO}_2 - \text{Al}_2\text{O}_3 - \text{CaO}$ (Nurnberg, 1981), show that a 10% addition of anorthite is sufficient to lower the slag melting point below that of the iron product.

The overall process chemistry in the plant is:



This is composed of the following steps (not showing partial reduction of TiO_2):



In the smelter, feed material is mixed with a carbonaceous reductant and heated until melting, reduction, and slag/metal separation take place. The reductant should be as hydrogen poor as possible to keep the volume of smelter off-gas down and to reduce heat loss in this stream. The reductant is recycled carbon, reformed from monoxide to waxes by Fischer-Tropsch synthesis and is perhaps cracked (4,5). Unfortunately, these waxes do not coke well, and research and development may be required to improve the yield of crackable products. The light ends can be reformed either by partial reoxidation or arc cracking to give materials more suitable for coking, at the cost of substantially increased power consumption.

Carbon is the refractory of choice for this reactor due to its high strength to weight ratio, its resistance to attack by the (titanium carbide saturated) iron product, and its availability from electrode wear, garbage, and the recycled off-gas. Carbon is used in terrestrial ilmenite smelters and, with the slag skull, is found to be semi-permanent in service (Noda, 1965). Some operating data are available (Knoerr, 1952; Noda, 1965; Grau and Poggi, 1978) from plants that use a thermal gradient stabilized slag skull to protect the refractory lining from chemical attack. Process power consumption is about 3.5 MWh/T Fe (megawatt-hours per ton of iron), and arc heating electrode consumption is between

562 / Oxygen: Prelude to Lunar Industrialization

5 and 10 kg/T Fe, which translates to converting about 0.75% of the carbon flow in the total process into electrodes. Arc heating uses low voltage DC power like that generated in photovoltaic or nuclear thermionic processes.

Substantial research has been done on processes for iron production by introducing hydrocarbon, coal, or coke into a slag-metal bath (Eketorp *et al.*, 1981). Because reduction in the bath (2) is an endothermic process, it has not proven possible to get rapid reaction on the scale of typical terrestrial iron reduction furnaces (10,000 tons of hot metal produced per day). However, calculations indicate that heat transfer in the bath is more than adequate for the small scale of operation relevant to lunar iron reduction plants.

One advantage of smelting ilmenite is that under process conditions the titania will be partially reduced. This increases oxygen recovery per unit throughput and decreases the amount of iron that must be decarburized per unit oxygen produced. However, feed minerals for lunar iron production have low iron content compared to terrestrial ores, causing a high ratio of slag to iron and increasing the heat demands and reactor size per unit oxygen (or iron) production.

The pig iron product will contain carbon, and decarburization (3) is required to make a usable product and to obtain high carbon recycle efficiency. Decarburization could employ steam, oxygen, or wet hydrogen. Low lunar gravity is helpful to decarburization by allowing longer gas/liquid contact times. Steam decarburization is endothermic and thus would not lead to hot spots in the bath or the severe refractory wear associated with oxygen decarburization. Alternatively, oxygen decarburization is exothermic, so the vessel would need no heat source. The overall oxygen/steam ratio could be adjusted to bring the reactor into thermal balance. Although power availability and materials arguments imply that consumable electrode arc heating would be the most practical approach to heat introduction, induction heating, which also removes the need for hydrocarbon cracking and electrode production, is possible. Modern induction power converters have masses ranging from 2 metric tons at 1MW to 3.5 metric tons at 2MW. Conversion efficiency is typically 96%, adding 40–80 kW to the heat load that must be rejected at low temperatures.

Counter-current heat exchange between pelletized feed and reactor off-gas in a moving bed could decrease the electrical energy requirement. It would also cool the off-gas to suitable temperature for subsequent processing and would condense volatile impurities.

Both the decarburization and reduction off-gases will contain sulfur that could poison the Fischer-Tropsch catalysts. The best solution is to use resistant catalysts, or else to pass the off-gases through a water spray made basic by alkali oxide fumes. (This water spray is a small added inventory of water on its way to the electrolyzer.)

Water is a by-product of Fischer-Tropsch synthesis; its electrolysis (6) leads to the product oxygen, which is liquified and stored. Electrolysis has been extensively studied in a space context. Literature also exists on using thermal cycles for production of hydrogen and oxygen from water, often using solar heat. Thermal water-splitting, if available, would significantly reduce electrical power demands. Although processes making direct use of solar radiation are known (Raissi and Antal, 1985), further research and design studies are needed.

SYSTEM CONSIDERATIONS

A variety of considerations apply to any system involving the production of oxygen on the Moon and its delivery to Earth orbit. Tradeoffs must be made involving solar versus nuclear power supply and continuous versus batch processing. Systems design and economic criteria will be quite different if a lunar oxygen producing plant is installed before a lunar base or as part of a lunar base program.

A coexisting lunar base would have several beneficial effects on lunar factory operations and economics, since routine and non-routine repairs could be attended to quickly and would be a marginal cost (the marginal cost of extra person-hours) rather than a direct cost with the addition of transport charges. Propellant oxygen for transportation from the Moon is an economical product even under circumstances where lunar oxygen export to Earth orbit may prove uneconomical. Inexpensive plant by-products, such as cast slag bricks or formed steel parts, may have some utility and economic value at the lunar base.

Without a coexisting base, reliability would become very important and would have to be ensured even at a high cost in mass or initial factory cost. One simple means of enhancing product supply reliability is to install over-capacity, so that unexpected downtime does not deplete product stores. Another approach is to have redundant plant elements so that unscheduled maintenance does not stop all production. The costs and benefits of over-capacity are obvious. The change in capacity required for reasonable reliability (10–20%) is not enough to affect the plant systems design substantially. Redundancy may be a different story because the total capacity is shared by multiple small plants. Since plant masses (and capital costs) scale according to the $2/3$ power of capacity, the ratios of costs for no redundancy, dual redundancy, and triple redundancy are 1:1.26:1.44.

For a carbothermal oxygen plant, the reduction in capacity of each process reactor with increased redundancy means that the smelting reactor will become more difficult to operate in a continuous mode. The costs of batch and continuous processes scale differently, with large scale favoring continuous processing. Continuous operation is very desirable on the Moon due to the ease of automation and automatic control, simplified design, lower thermal cycling, and facile use of gravity feed when compared to batch processing. If the capacity reduction needed to make redundant oxygen factories forced a transition from continuous to batch smelting, the capital cost penalties would increase substantially. Electrolysis, reforming, and cracking units are operated economically on Earth in continuous mode on a scale similar to that necessary for a lunar factory capable of producing 1000 tons of oxygen per year. Despite possible increased costs, redundancy is very effective in reducing the likelihood of unexpected supply interruptions if a plant must be operated at an unmanned lunar facility. Single versus redundant plants must be traded off in any systems study of lunar oxygen production at an unmanned facility.

Continuous process ilmenite smelters are operated on Earth at 10–20 times the capacity needed in a 1000 ton per year of oxygen lunar factory, but the thermal balance in these

564 / Oxygen: Prelude to Lunar Industrialization

Table 1. Energy and Power Requirements per Ton of Product Oxygen

Process Step	Energy (GJ)
Reduce 3.68 tons of iron (75% efficiency)	12.1
Heat to melt 3.68 tons of iron (500 kWh/ ton)	6.6
Heat content of 4.25 tons of slag (470 kWh/ ton)	7.2
Heat content of off gas (1350 oC effective heating)	8.0
Energy to electrolyze water (60% efficiency)	28.9
Energy to liquify oxygen	5.4
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Total energy consumption, carbothermal process	68.2
Total power requirement for 1000 tons of O ₂ per year (100% duty cycle)	2.16 MW
Nuclear power plant capacity (90% duty cycle)	2.40 MW
Solar power plant capacity (40% duty cycle)	5.40 MW

Methane reductant, no heat regeneration.

Data scaled from that presented by Rosenberg *et al.* (1965f) for a 12,000 lb/mon oxygen production facility without heat pumping. Power was assumed to scale linearly.

smelting units is delicate. The possibility of scaling a continuous smelting reactor down to the capacity needed for carbothermal production of lunar oxygen must be the subject of further study.

In contrast, all terrestrial steel-making is done in batch processes. Capacities up to several hundred tons of steel per hour are common. It seems unlikely that lunar steel-making can be done in a continuous mode.

Manufacturing plant power demand will be several megawatts (Table 1), well in excess of power demand for other functions of a lunar base. Nuclear energy is likely to be used to power a manned surface facility, due to the difficulty of storing solar derived energy for use during the lunar night. Continuous energy supply may not be a requirement for a lunar factory. Since factory power demands are much higher than and have a different time phasing and quality from other power demands, a total systems design will be required to select the optimum power system for the complex. In fact, the factory and base may have separate power systems.

There are two competing factors in the tradeoff between solar and nuclear energy for the lunar factory power supply: (a) the relative power to mass ratios of solar and nuclear power systems, and (b) the overall plant masses required to produce a given amount of product when the power supply and plant duty cycles are taken into account. Plant mass breakdowns for solar and nuclear powered plants are given in Table 2. The simple assumptions used in this table give solar and nuclear powered plant masses that are essentially equal. Accurate projections of solar and nuclear power system power to mass ratios as well as accurate scaling laws derived from careful design studies will be needed before any decision can be made about the selection of power sources.

The delivery of a lunar oxygen factory to the Moon's surface and the storage and transportation of lunar oxygen are separable from the lunar oxygen manufacturing plant itself in a systems sense. Transportation system characteristics are more likely to be

Table 2. Processing Plant Mass per Unit Output of Product

Product	100% Duty Cycle		90% Duty Cycle		40% Duty Cycle	
	Oxygen	Iron	Oxygen	Iron	Oxygen	Iron
Processing plant	30.4	8.69	32.6	9.32	56.0	16.0
Mining and beneficiation	10.8	3.09	12.0	3.43	27.0	7.7
Oxygen plant mass			44.6		83.0	
Power plant (Table 1):						
Nuclear (40 W/kg)			60			
Solar (190 W/kg)					28.5	
Total mass			104.6		111.5	

In tons per 1000 tons per year.

Data scaled from that presented by Rosenberg *et al.* (1965f) for a 12,000 lb/month oxygen production facility without heat pumping. A decarburization reactor (taken as equal in mass to the reduction reactor) was added. Decarburization is assumed to consume 5% of the ultimate O₂ production. Plant mass is assumed to scale as the 2/3 power of capacity.

determined by space station and lunar base needs than by lunar oxygen factory needs. Nevertheless, there exists a design interaction between maximum size and mass of factory components and the payload capacity of the transportation system.

DISCUSSION

The carbothermal reduction process has been discussed in an appropriate thermodynamic context, and plant mass and power estimates have been made (Rosenberg *et al.*, 1965f). Mass estimates (Table 2) are 32.6 tons of plant and power requirements equal to 60 tons of 1990 (projected) nuclear power supply and mining and beneficiation equipment of about 12 tons per 1000 tons of oxygen production per year. Mining equipment mass is taken from Gertsch (1983), and beneficiation is assumed to be similar to that reported by Agosto (1985). Assuming a mass ratio of iron to oxygen of 3.5:1 (as for stoichiometric oxide), these correspond to 9 tons of plant supply, 17 tons of power supply, and 3 tons of mineral handling equipment per ton of steel produced per day in an ilmenite smelting process.

The carbothermal process for lunar oxygen production and a process based on the hydrogen reduction of ilmenite bear the same relationship to each other as direct reduction and smelting do in terrestrial engineering. It is thus reasonable to expect them to be competitive technologies as they are on Earth.

The hydrogen reduction process reacts the mined ilmenite with hot hydrogen to produce water, iron, and rutile. The water is electrolyzed to produce oxygen and regenerate hydrogen. Thermodynamic equilibrium limits the per pass conversion of hydrogen to water to about 5%. Subsidiary hydrogen reduction of ilmenite produces an intimate mixture of iron and rutile and would require a subsequent thermal processing step to separate the iron.

566 / Oxygen: Prelude to Lunar Industrialization

There are several factors that seem to favor the carbothermal reduction based process. Makeup carbon is available from a variety of sources, such as garbage and scrap. Hydrocarbons and carbon are much easier to handle than hydrogen. This is particularly significant when some reagent inventory must be kept on hand for makeup between supply deliveries from Earth. As process temperature increases, significantly more oxygen can be recovered from a given weight of ilmenite. Reduction carried out under slagging conditions will only require 1/2 to 2/3 as much ilmenite per unit oxygen recovery as would subsolidus reduction at 700°C–900°C.

The major problem with hydrogen reduction of ilmenite appears to be the unfavorable equilibrium constant for the conversion of hydrogen to water. This ranges from 0.031 at 600°C (Williams, 1983) to 0.117 at 1300°C (Shomate *et al.*, 1946). If the hot, wet hydrogen is cooled down to condense out the water and then reheated, an excessive heat demand is imposed on the system. Developing a high temperature electrolysis cell using a ceramic oxide ion conductor to dewater the hydrogen without cooling it adds development costs and risks. In contrast, carbon reacts completely in a single pass. It also extracts more oxygen from ilmenite in a single pass than does hydrogen on a mass basis. (A mass unit of carbon extracts 1.33 to 1.45 mass units of oxygen per pass, while a mass of hydrogen extracts 0.25 to 0.94 mass units of oxygen per pass, depending on the equilibrium conversion limit.)

The following processes that have been proposed to extract oxygen from lunar material cannot be compared directly with the carbothermal process but are considered to have significant technical weakness:

1. Electrolysis of molten lunar minerals has been studied as an oxygen producing process. However, no anode material tried to date has clearly demonstrated adequate corrosion resistance (Haskin and Lindstrom, unpublished data, 1984), leaving some possibility that the process is impractical.

2. Vapor phase pyrolysis of lunar minerals involves vaporizing lunar soil or selected mineral separates and then rapidly quenching the vapor. The hot gas contains some metal atoms and oxygen molecules. Literature data (Borgianni *et al.*, 1969) make it seem unlikely that quenching of the hot gas can be made rapid enough to prevent loss of oxygen through reoxidation.

3. The hydrofluoric acid leach process as described by Waldron (1985) involves dissolving bulk lunar soil in a fluoride based acid, separating the resulting mixed salt solution into pure metal fluorides, reducing these metal fluorides with sodium and potassium, hydrolyzing the resulting alkali fluorides to regenerate hydrofluoric acid, and producing oxygen by electrolysis of molten alkali hydroxides. Design-based mass estimates are 77 tons of plant per ton of soil input per day, or 586 tons of plant per thousand tons of oxygen per year (assuming 40% oxygen by mass of lunar soil and a 90% duty cycle), much higher than for competing processes.

RESEARCH NEEDS

Conceivably, fatal flaws could exist in the carbothermal process in any of three areas where research is badly needed: (a) kinetics and phenomenology of (simulated) lunar

ilmenite reduction, (b) carbide solubility in typical slags, and (c) iron decarburization. Experimental data on these key issues would narrow design uncertainties in the two least well understood parts of the system, the smelter and the steel-making reactor.

Once it has been verified that the basic process chemistry for carbothermal production of lunar oxygen is sound, the following secondary research projects would define system performance and design. A Fischer-Tropsch catalyst is needed that gives readily crackable product with a low H to C ratio and which is also economical in the lunar context. Appropriate hydrocarbon coking and electrode production techniques need development. Thermal methods of producing hydrogen and oxygen from water should be explored and traded off against electrolysis in system design studies. Various methods of heat rejection and thermal control should be studied and compared to each other at the system level. All of the above studies would have to be performed to determine whether plant development is warranted.

The choice between a nuclear or a solar powered system depends on the relative power-to-mass ratios and on the plant mass scaling law. The tradeoff seems close now and cannot be resolved without careful systems studies shortly before plant emplacement.

Separating water into hydrogen and oxygen by thermolysis is an interesting possibility for a carbothermal process plant and for a variety of other types of plants. Water thermolysis should be examined in a space context independently of other projects.

A lunar oxygen factory in the context of a lunar base program can be the source of inexpensive by-products (slag and steel) that would be very useful to the base. The properties of slag or steel manufactures cannot be predicted solely on the basis of compositional data. If these by-product materials were to be useful in lunar base activities, their properties would have to be determined experimentally using simulants of appropriate composition.

If development seems to be a possibility, the interface between the oxygen producing factory (after the oxygen liquifier) and the storage and transportation system will have to be studied. If the oxygen storage facilities on the lunar surface are considered part of the transportation system, parameters such as mission frequency have practically no effect on the oxygen producing plant, and few plant parameters have any effect on the transportation system.

CONCLUSIONS

Carbon is an economical reductant in the lunar context because it removes more than 1.25 times its mass of oxygen per pass. Hydrogen, though lighter per mole, only removes 0.4–0.9 times its own mass per pass due to thermodynamic limitations. Makeup carbon might be readily available from spent factory delivery stages, scrap, or lunar base garbage.

Thus the carbothermal route to lunar oxygen is economically and technically attractive. There is low technical and performance risk in plant design and development due to extensive Earth-based experience with each element of the process. The basic research needed to demonstrate the feasibility of this concept is straightforward and well defined. It consists of quantifying carbon loss in slag and steel and studying process behavior

568 / Oxygen: Prelude to Lunar Industrialization

in the reduction reactor. Further definition should be pursued, both in the laboratory and through selected system studies.

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