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An Annotated Bibliography of Propellant Processing Methods

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Dr. Cutler has specialized in space resources research for many years, with special emphasis on oxygen reduction methods. He has been retained to write a comprehensive review of these methods, detailing advantages and disadvantages, listing byproducts, and presenting recommendations. As the first step, an extensive outline was prepared, and the portion of this outline covering product manufacture was selected as the initial goal. A working version of this section follows:

## Products

## I. Propellant

## A. Oxidizer

## 1. Oxygen

## a. Production from lunar materials

## i. Slagging carbothermal

- of ilmenite
- of olivine
- in integrated polyelement processes

## ii. Subsolidus reduction

- ilmenite with  $H_2$  or C
- olivine with  $H_2$  or C

## iii. Plasma processes

- with  $H/H_2 + FeO \cdot XO_2$
- with  $Cl/Cl_2 + FeO \cdot XO_2$

## iv. Slog electrolysis

- bulk soil
- mineral separates
- with fluxes (Kesterk, EMEC)

## b. Production from asteroidal/Phobos/Deimos meet?

## i. Water splitting

- electrolysis
- photolysis
- thermolysis

ii.  $CO_2$  processing

- solid state electrolysis
- carbonate? melt electrolysis

iii. Oxide reductions, e.g.,  $FeO + (CH_2)_n$ 

## c. Production on Mars surface—variants of processes above

## 2. Peroxide

- a.  $\text{H}_2\text{O}_2$  via  $\text{Na}_2\text{O}_2$
- b. Direct  $\text{H}_2 + \text{O}_2$
- c. Electrochemical means from  $\text{O}_2$
- d. Water partial oxidation

## 3. Nitrogenous oxidizers

- a. Organic N  $\rightarrow$   $\text{NH}_3$
- b. Organic N  $\rightarrow$   $\text{N}_2$
- c.  $\text{N}_2 \rightarrow \text{NH}_3$
- d. Organic N  $\rightarrow$  NO
- e.  $\text{NH}_3 \rightarrow \text{NO} + \text{H}_2\text{O}$
- f.  $\text{NO} \rightarrow \text{NO}_2$
- g.  $\text{NO}_2 + \text{H}_2\text{O} \rightarrow \text{HNO}_3$
- h.  $\text{N}_2\text{O}_4$
- i. RFNA

## B. Fuels

## a. Hydrogen

- i. From lunar soil
- ii. From asteroidal materials via hydrocarbons
- iii. Various routes from water (see above)

## b. Hydrocarbons

- i. Direct from asteroids phobos and demo
- ii. Reformed from initial pyrolyzate
- iii. Fischer-Tropsch synthesis from  $\text{CO} + \text{H}_2\text{O}$
- iv. From  $\text{CH}_3\text{OH}$

## c. Oxygenates--alcohols, ethers, etc.

- i. Methanol from  $\text{CO} + \text{H}_2$
- ii. Higher alcohols from  $\text{CO} + \text{H}_2$
- iii. Hydrocarbons  $\rightarrow$  oxygenates

## d. Hydrocarbon--hydrogen mixtures

(solubility of  $\text{H}_2$  in various materials)

## e. Metals

- i. Al
  - ii. Mg
  - iii. Ca
- } see metal production below

## f. Metal/liquid mixtures

- g. Nitrogenous fuels
  - i. Ammonia (see above)
  - ii. Hydrazines from ammonia
    - $\text{Cl}_2$  process
    - $\text{O}_2$  process
    - organo substituted hydrazines
- C. Thermal propellants
  - 1. Hydrogen (see above)
  - 2. Ammonia (see above)
  - 3. Hydrozine (see above)
  - 4. Others
- D. Electric propellants
  - 1. Calcium and potassium
  - 2. Compounds— $\text{Cl}_2$ ,  $\text{SO}_3$ , etc.
- E. Mars propellants
  - 1. Hydrogen peroxide (see above)
  - 2. Hydrozine (see above)
  - 3. Fuel/oxidizer solutions
    - a. Hydrocarbon—oxygen
    - b. Peroxide/alcohol or peroxide/hydrocarbon
  - 4. Metal/sulfur propellants ( $\text{MgS}$ ,  $\text{CaS}$ )
- II. Structural Materials
  - A. Metallic
    - 1. Ferrous ( $\text{Fe}$ ,  $\text{Ni}$ ,  $\text{Co}$ )
      - a. Fe—steel
        - i. From magnetic collection
        - ii. From subsolidus reduction
        - iii. From slogging
      - b. Iron alloys
        - i. Imported alloying additions
        - ii. Local source
      - c. Forming and heat treating
        - i. Forging
        - ii. Casting
        - iii. Machining
        - iv. Carboxyl deposition

**2. Non-ferrous metals****a. Aluminum****i. Winning**

- carbochlorination
- plasma chlorination
- fluorination
- integrated processes

**ii. Forming**

- cast
- roll
- forge
- machine

**iii. Alloying additions**

- local source--Mg, Mn
- imported--Zn, Cu

**b. Magnesium****i. Winning**

- carbothermal
- salt electrolysis
- plasma processing

**ii. Generation of MgO feed****iii. Forming (as for aluminum)****iv. Alloying additions****3. Vacuum refining****a. Advantages and effects on properties****b. Effect on local environment****4. Tool materials****a. Tool steels--composition and properties****b. Titanium carbide tool materials--cobalt bonded****i. Cobalt source****ii. Other binders****5. Brazes and solders****a. Aluminum, magnesium, and calcium as vacuum brazes****B. Non-metallic****1. Bricks****a. Mortar bound****b. Cut stone**

- c. Sintered
  - d. Slogged and cast
    - i. Glass
    - ii. Ceramic
- 2. Bogs
  - a. Wire
  - b. Glass
- 3. Beams and pillars
  - a. Fused soil
  - b. Sintered
  - c. Mortered
  - d. Packed form
- 4. Fibers--glass
- 5. Refractories
  - a. Graphite
  - b. Magnetite and CaO
  - c. CaS and MgS
  - d.  $\text{Cr}_2\text{O}_3$
  - e. Titanium oxides
- 6. Cements
- 7. Inorganic Polymers
- 8. Sulfur

### III. Explosives

- A. Fuel/oxidizer explosives
  - 1. Fuel/ $\text{H}_2\text{O}_2$ 
    - a. Organic
    - b. Metallic
  - 2.  $\text{NH}_4\text{NO}_3$  + fuel
- B. Nitrates from oxygenated organics and nitric acid