19890005477

N89-14848

56-91

175152

180

PROCESSES AND ENERGY COSTS FOR MINING LUNAR HELIUM-3

I.N. Sviatoslavsky

W4560409

Fusion Technology Institute
and
Wisconsin Center for Space Automation and Robotics
University of Wisconsin - Madison
Madison, WI 53706

PRECEDING PAGE BLANK NOT FILMED

E-4245

PAGE 128 INTENTIONALLY BLANK

SUBJECTS COVERED:

1) Mining and Extraction Processes:

•Excavating •Conveying •Beneficiating •Heating •Energy Recovery •Redeposition	Lunar Regolith
•Collecting •Condensing •Transporting	Solar Wind Products

2) Masses of Equipment Required

3) Process Power Requirements

4) Energy Payback

Solar Wind Gas Release Predicted for Maria Regolith When Heated to 700°C

	He3	He4	H_2	Carbon	N_2
Concentration in Maria regolith (ppm or g/tonne mined)	9×10^{-3}	30	50–60	142–226	102–153
Concentration in Grains < 50 μ (g/tonne mined)	8.1×10^{-3}	27	50	166	115
Amount Released at 700°C (g/tonne mined)	7×10^{-3}	22	43 (H_2) 23 (H_2O)	13.5 (CO) 12 (CO_2) 11 (CH_4)	4
Mass Obtained per kg of He3 (tonnes)	10^{-3}	3.1	6.1 (H_2) 3.3 (H_2O)	1.9 (CO) 1.7 (CO_2) 1.6 (CH_4)	0.5

Prime Considerations in the Design of Lunar Miner Mark-II

- **Efficient utilization of lunar regolith as a source of He-3 implies deep mining, down to 3 meters.**

- **Disposition of rejected and processed regolith during and after mining to minimize impact on the lunar landscape.**

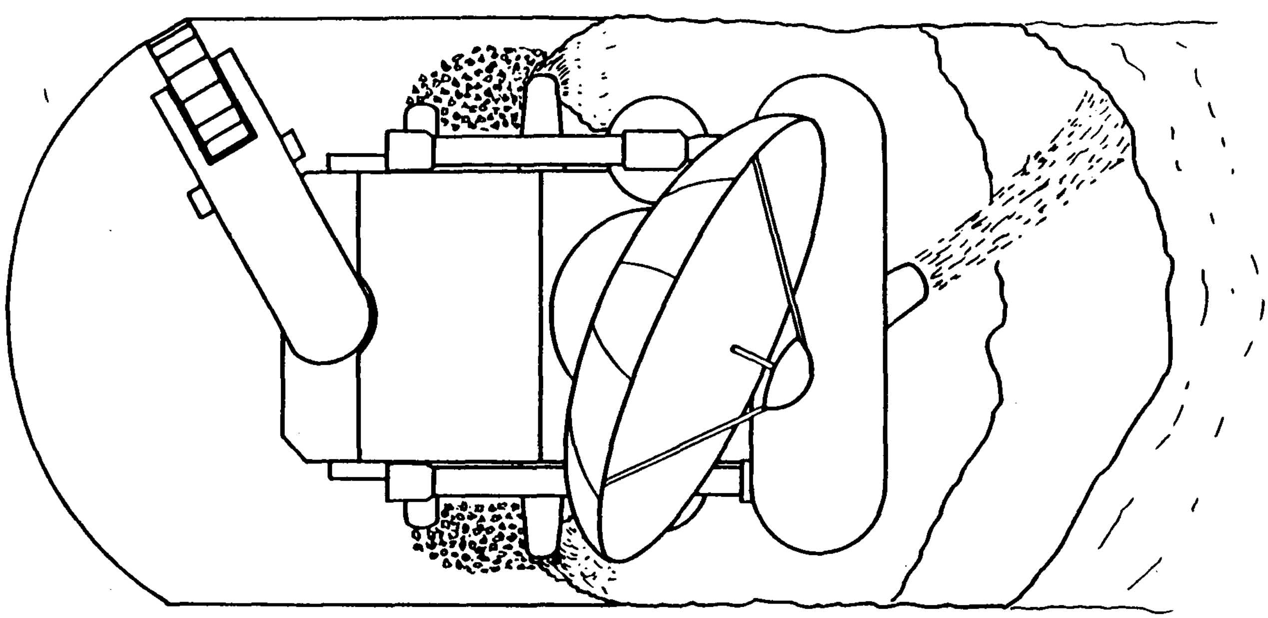
Convenient gas handling.

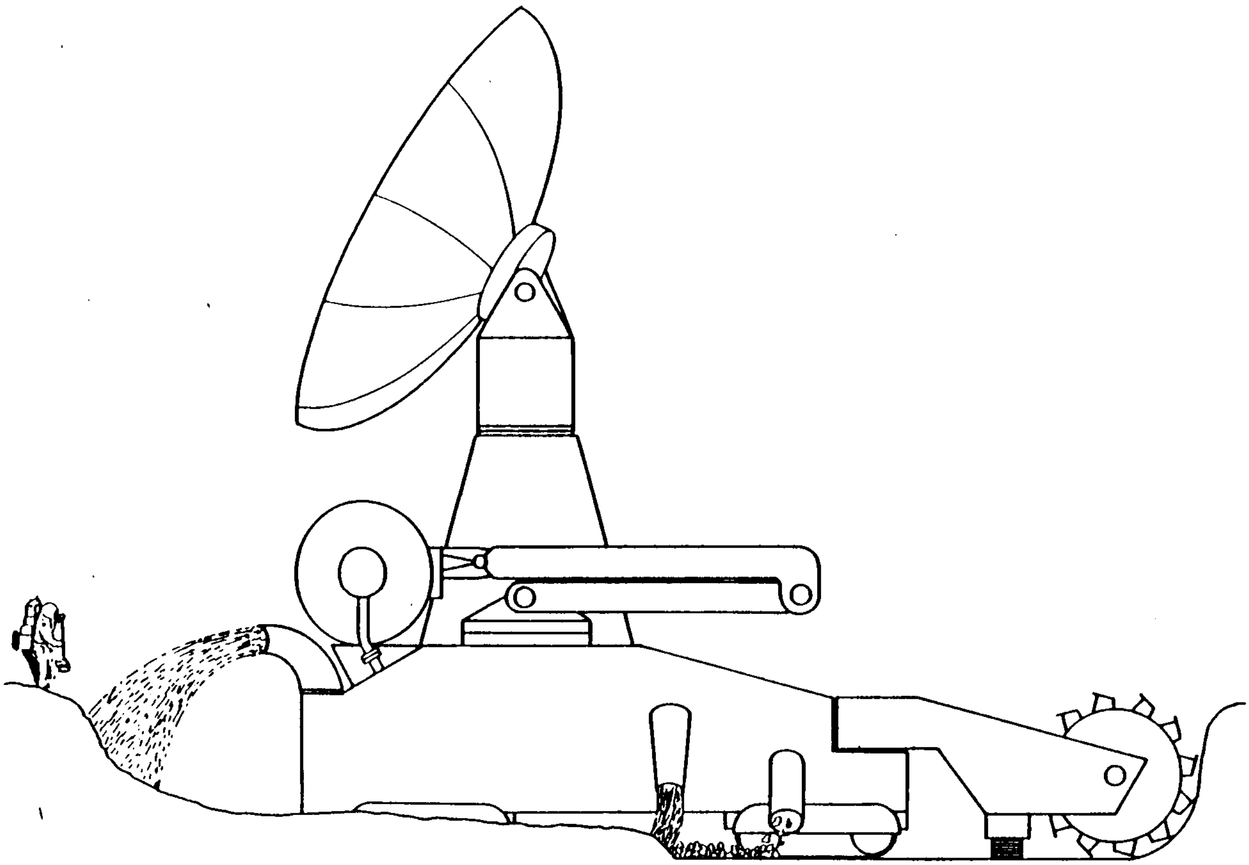
- Use of a bucket wheel excavator for excavating a deep wide trench.

- Deposit rejected regolith along the sides of the miner and eject the processed regolith from the back to refill trench uniformly.

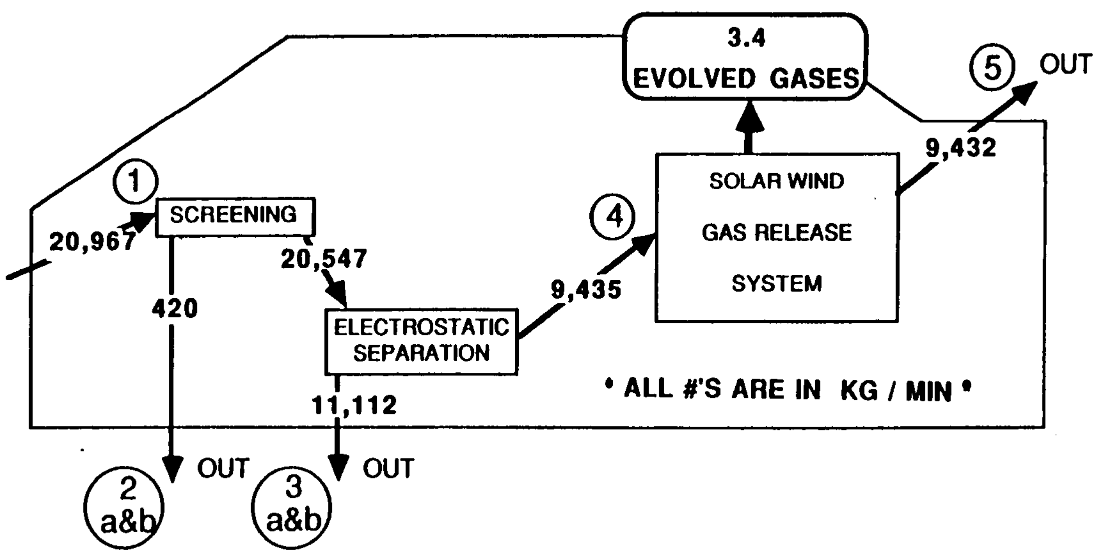
- Service vehicles place empty gas cylinders along one side of intended mining route.
  Miner picks up cylinders one at a time and deposits full ones on the other side of trench.
  Service vehicles pick up full cylinders and transport them to condensing station.

TOP VIEW OF LUNAR MINER MARK-II





SIDE VIEW OF LUNAR MINER MARK-II



NOTE: NO.'s IN CIRCLES REPRESENT INTERNAL REGOLITH CONVEYOR NO.

FIGURE C. REGOLITH MASS FLOW RATES (kg/min)

Conveyor System Characteristics

Conveyor Number	Vert./Horiz. Displacement (m)	Belt Speed (m/min)	Mass Transport Rate (kg/min)	Mass of Conveyor (kg)	Power Required (kW)
1	0.5/1.25	15.4	20970	120	2.35
2a & b	-0.25/2.0	0.2	210	418	0.03
3a & b	-0.25/2.0	4.1	5767	418	0.68
4	2.25/3.5	6.9	9437	479	1.4
5	0.5/1.5	6.9	9437	187	0.76

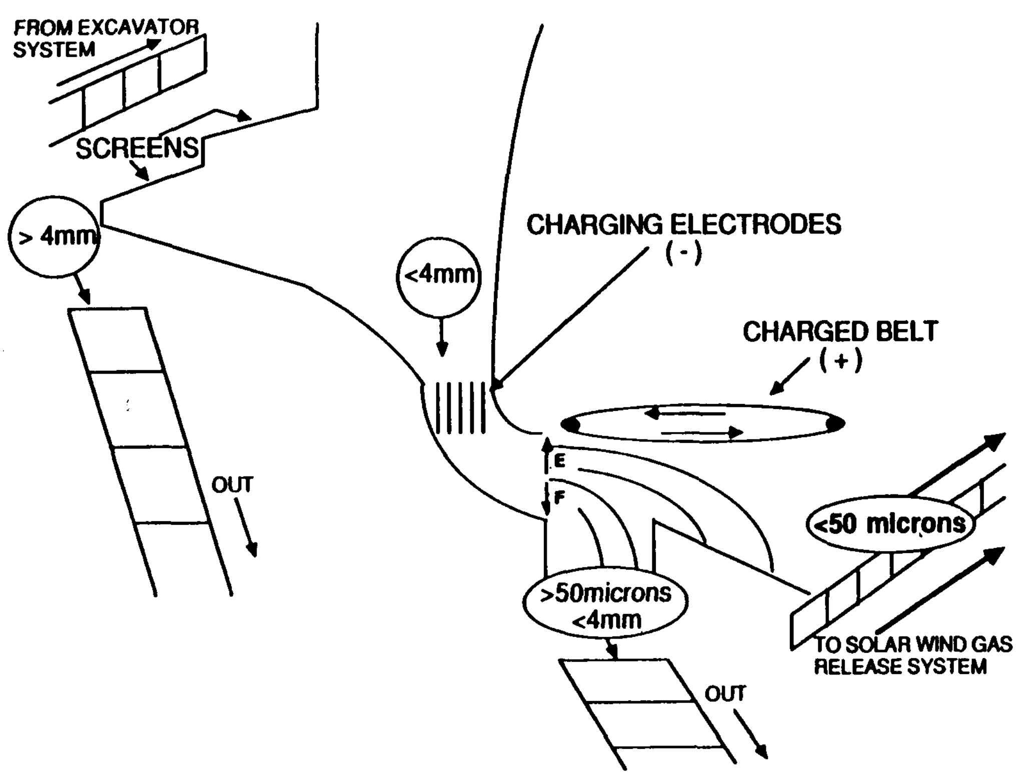


FIGURE B. INTERNAL REGOLITH BENEFICIATION SYSTEM

Heater Design

- Regolith processing rate is limited by energy supply, making heat recovery mandatory

- The heater is designed with a preheater, supplemental heater and a recouperator, achieving 85% energy recovery

Heating of Regolith

University of Wisconsin

ASSUMPTIONS

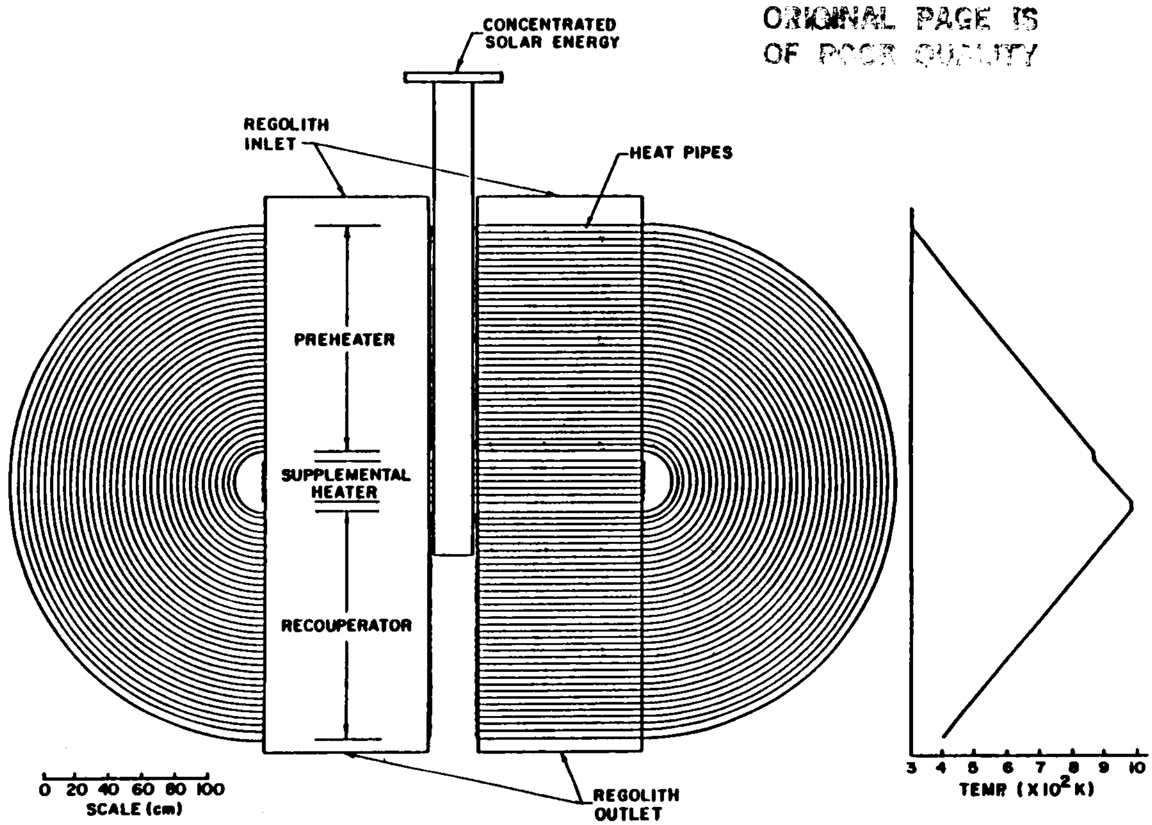
- Solar energy beamed from 110 m diameter solar collector to a 10 m diameter dish mounted on miner

- Oven enclosure will have 0.1 – 0.2 atm of solar wind products

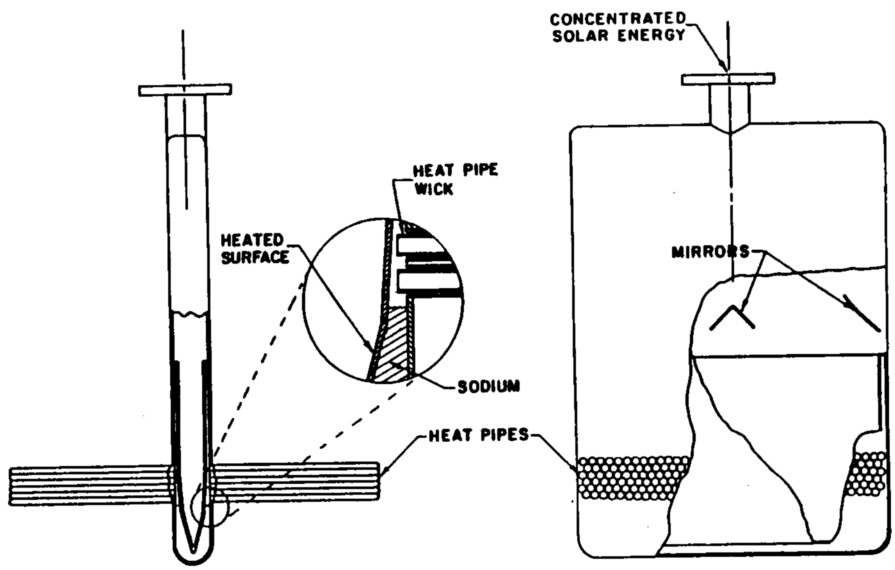
Deissler Boegli method used to determine effective thermal conductivity of regolith

- Dietus Boelter formulation used to obtain heat transfer coefficients: these were benchmarked against UW experiments performed in 1980–82 with remarkable agreement

ORIGINAL PAGE IS
OF POOR QUALITY



VIEW OF REGOLITH HEATER AND A REGOLITH
TEMPERATURE PROFILE AS A FUNCTION OF HEIGHT



TWO VIEWS OF SUPPLEMENTAL HEATER

Gas Collection System Compressor

Compressor Type	Reciprocating
Inlet Pressure (MPa)	0.02
Outlet Pressure (MPa)	15
Number of Stages	6
Power Requirement (kW)	160
Estimated Mass (tonnes)	1.2

Selected Mobile Miner Parameters

Annual collection rate of He3 (kg)	33
Mining hours/year	3942
Excavation rate (tonnes/hour)	1258
Depth of excavation (m)	3
Width of excavated trench (m)	11
Forward speed of miner (m/h)	23
Area excavated per year (km^2/y)	1.0
Processing rate (tonnes/hour)	556
Process energy requirement (MW)	12.3

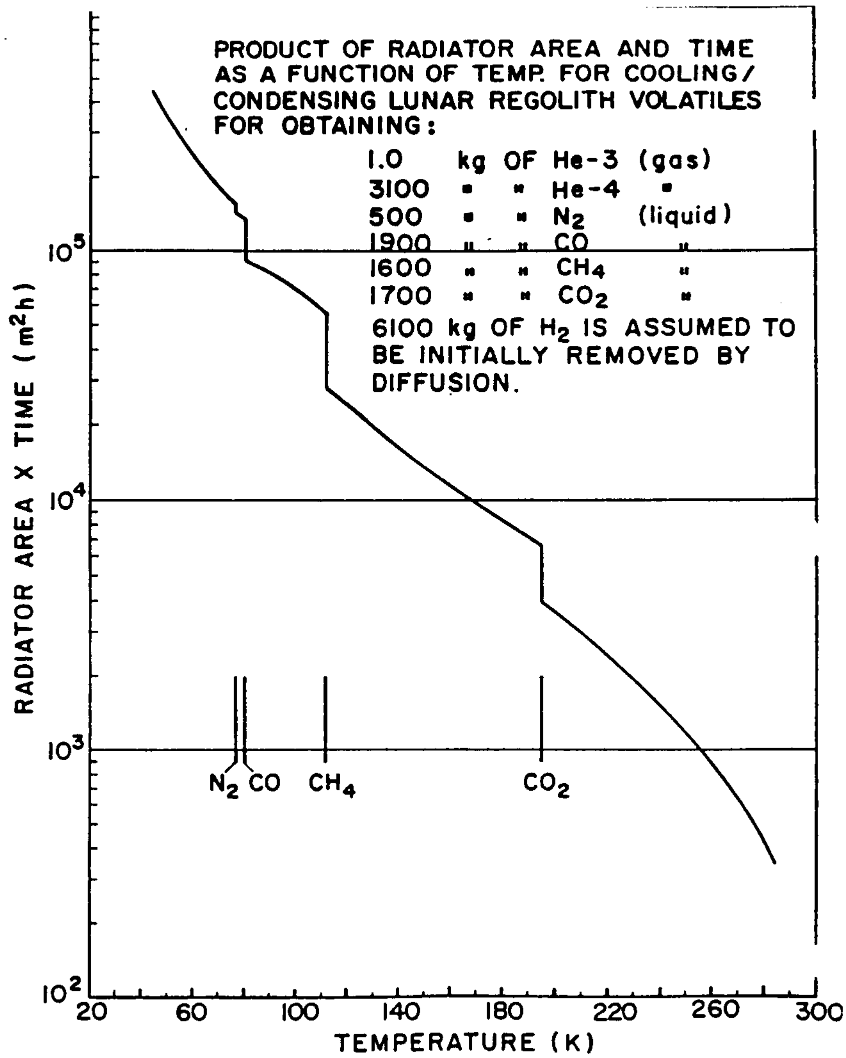
Selected Mobile Miner Parameters (contd.)

Heat recovery (%)	85
Number of conveyors required	5
Assumed inlet regolith temperature (K)	300
Maximum regolith temperature in heater (K)	973
Temperature of regolith deposited back (K)	400
Pressure in heater enclosure (MPa)	.02
Pressure of gases in cylinders (MPa)	15
Estimated operating power requirements (kW)	200
Estimated total earth mass of miner (tonnes)	18

Requirements of Radiator Area and Time for Cooling/Condensing Lunar Volatiles

Assumptions Made:

- H_2 gas removed prior to cooling by diffusion through a membrane within the gas cylinders
- Each species is drained out as it condenses
- Helium species are cooled to 55 K
- Radiator mass not included in cooling calculations
- Cooling takes place during lunar night



Radiator Area

- A radiator area of ~830 m^2 (29 m x 29 m) is needed to cool/condense solar wind volatiles (without H_2) to obtain a kg of He-3 per lunar month.

- The area needed is 6.9×10^5 m^2 (833 m x 833 m) to supply 10 tonnes of He-3 per year.

Cryogenerator Parameters

Inlet He Gas Temperature (K)	55
Outlet Liquid He Temperature (K)	1.5
Heat Rejection Temperature (K)	77
Percent of Carnot Efficiency (%)	17
Estimated Room Temp. Power (kW)	180
Liquid He Output (tonnes)	3.3
Availability (%)	50

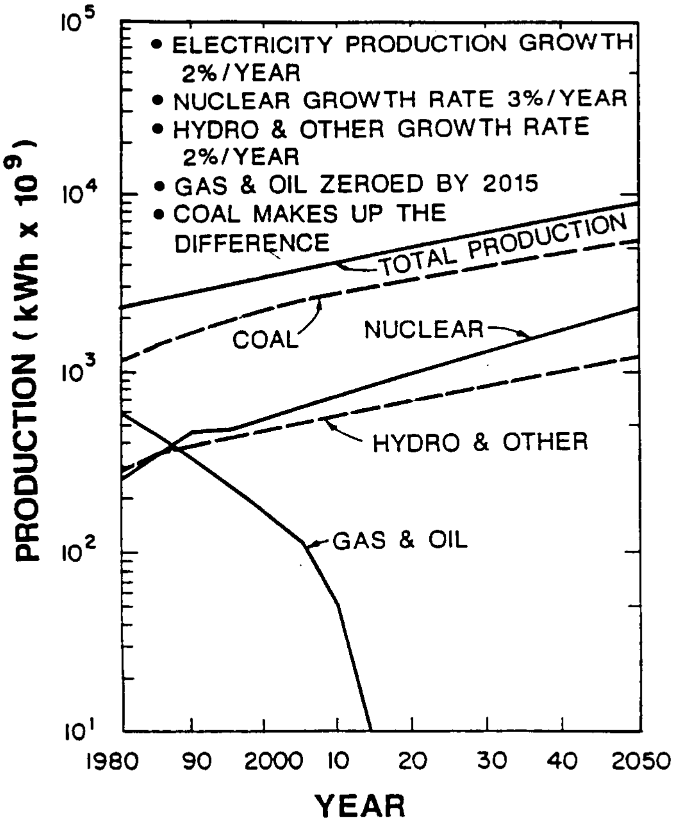
$^3He/^4He$ Isotopic Separation

1) Superleak Separator

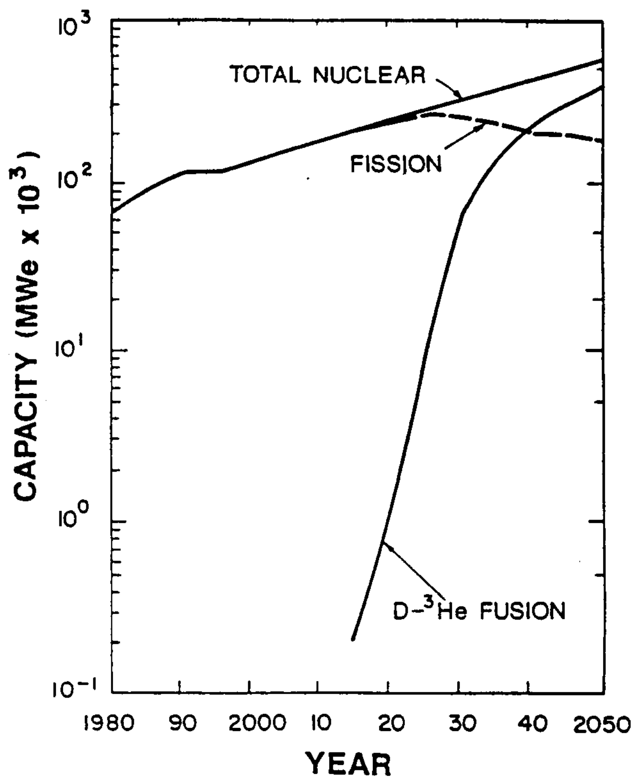
Temperature range: 1.5 K to 2.2 K
He-3 enrichment: 4×10^{-4} to $\sim 10^{-2}$

2) Cryogenic Distillation

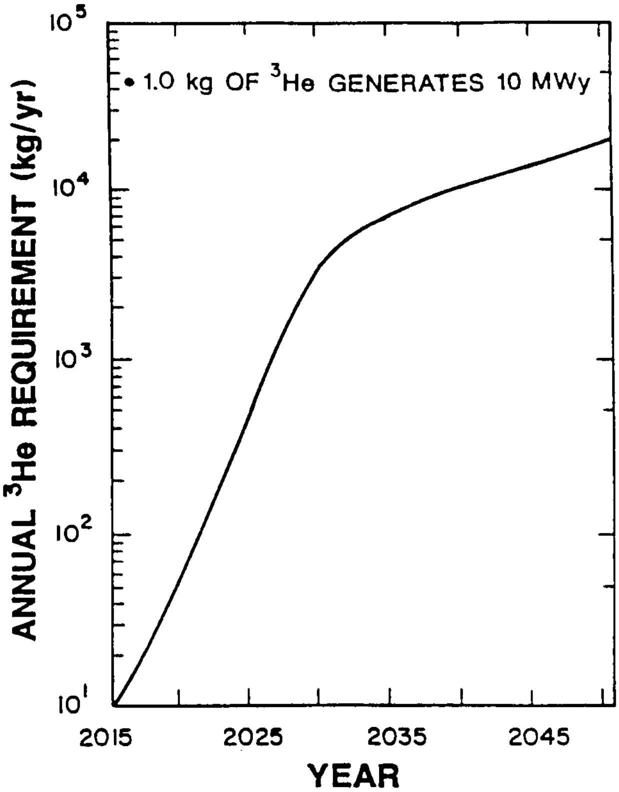
Temperature range: 2.3 K to 4.2 K
^{3}He enrichment: 10^{-2} to 0.99+



PREDICTED U.S. ENERGY DEMAND GROWTH RATE
(Low Growth Rate Scenario)

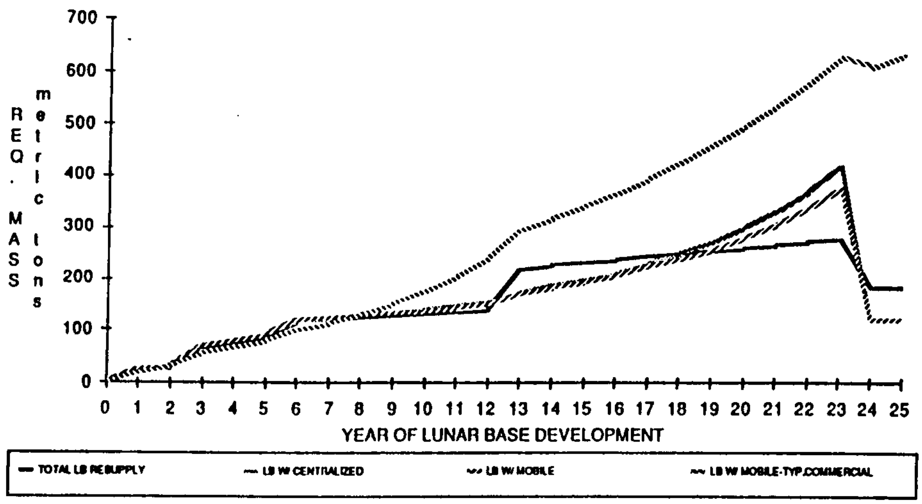


NUCLEAR CAPACITY SPLIT BETWEEN FISSION AND DHe-3 FUSION ASSUMING A 3% TOTAL NUCLEAR GROWTH RATE

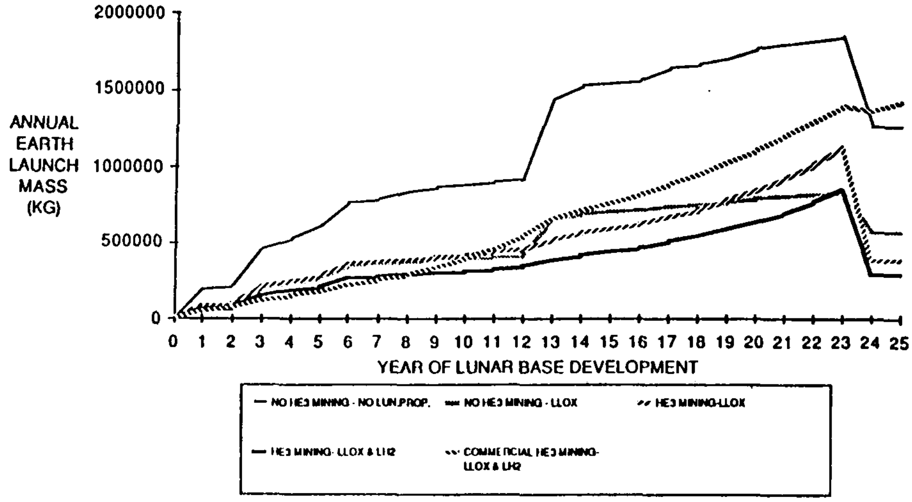


He-3 DEMAND CURVE

ANNUAL MASS DELIVERY REQUIRED AT THE LUNAR SURFACE FOR EVOLUTIONARY AND COMMERCIAL HE3 ACQUISITION SCENARIOS



ANNUAL EARTH LAUNCH MASS FOR BASELINE LUNAR BASE AND EVOLUTIONARY AND COMMERCIAL HE3 ACQUISITION SCENARIOS



Additional Resources Available from He3 Acquisition for Lunar Base Support

Resource	Application to Lunar Base	Estimated Requirement for 15–20 Person Base* (kg/y)	kg/miner-y
H_2O	Life Support Consumable	4280	$10.0x10^4$
O_2	Life Support Consumable	570	$7.7x10^{4}$(a)
N_2	Life Support Consumable	323	$1.7x10^4$
H_2	Lunar Resource Process Consumable	558	$20.1x10^4$

(a) O_2 obtained from additional processing of CO_2 and CO.

*Lunar base includes full scale mining operations, science facilities, semi-closed life support system, and MMW nuclear power source.

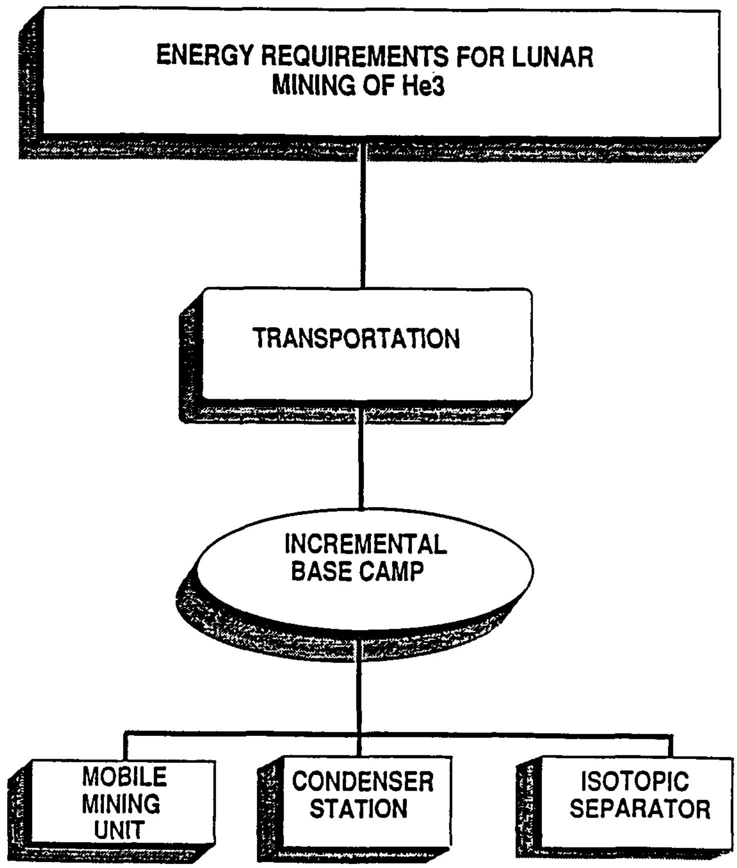


Figure 5

Operational Energy Requirements of Lunar Mobile Miner

Operation	Source	GJ/kg He-3
Locomotion & Excavation	Battery/ Solar	13
Conveyors & Beneficiation	Battery	4
Process Heat	Solar	4100 (free)
Compressor	Fuel Cell	67
TOTAL		84

OPERATIONAL ENERGY REQUIREMENTS FOR SEPARATING GASEOUS COMPONENTS FROM He3

OPERATION	SOURCE	GJ /kg HELIUM-3
H2 SEPARATOR	PERMEABLE MEMBRANE	VERY SMALL
ROBOTIC MANIPULATOR	BATTERY	1.6
GAS CIRCULATOR	BATTERY	0.5
LIQUIFIER (55 K TO 1.5 K)	PHOTOVOLTAIC	184
	TOTAL	186

TOTAL ENERGY REQUIRED TO BRING MINING EQUIPMENT AND HUMANS TO THE MOON

EQUIPMENT	EARTH MASS-kg PER kg He3 @	ENERGY TO BRING MASS TO MOON-GJ@@
MOBILE MINER	27	810
SERVICE VEHICLE	0.8	24
SOLAR MIRROR	12.4	372
RADIATOR/CONDEN.	9.0	270
He LIQ. &SEPARTOR	4	120
BASE CAMP EQUIP. (INCREMENTAL)	12.9	387
TOTAL	66.1	1983

@AMORTIZE OVER PRODUCTION OF 1 TONNE OF He3/YEAR FOR 20 YEARS
@@-30 GJ/kg TO TRANSPORT FROM EARTH TO MOON(INCL ROCKET AND CREW) AND RETURN WITH He3 TO EARTH

Total Energy Invested to Obtain and Transport 1 kg of He-3 to Earth

Operation	GJ
Transportation of Equipment	1983
Gas Separation	186
Mobile Miner (operations)	84
TOTAL	2253
Energy Released from 1 kg He-3	600,000

Energy Payback Ratio for Mining Helium-3

Defined as =

$$\frac{\text{Energy Released by burning 1 kg He-3 with 0.67 kg of } D_2 \text{ on earth}}{\text{Sum of the total energy required for transportation + base camp + mining operations + gas separation + isotope separation}}$$

Payback Ratio is =

$$\frac{600{,}000 \text{ GJ}}{2253 \text{ GJ}} = 266$$

If we include energy used to manufacture the materials for building the fusion reactor:

Based on 1985 study by R. Bünde, "The Potential Net Energy Gain from DT Fusion Power Plants", Max Planck Institut für Plasmaphysik, Garching, Federal Republic of Germany, June 1985

$$4188 \text{ MWh}_{\text{th. equiv.}} / \text{MWe} \cdot 30 \text{ y}$$

We get:

Fusion Plant	5025 GJ/kg
He-3 fuel	2253 GJ/kg
TOTAL	7278

$$\text{Total Energy Payback} = \frac{600{,}000}{7278} = 82$$

Conclusions

- Preliminary investigations show that obtaining He-3 from the moon is technically feasible and economically viable.

- With the exception of beneficiation, the proposed procedures are state of the art.

- Mass of equipment needed from earth is of some concern, but resupply will eventually be ameliorated by the use of titanium from indigenous ilmenite.

- A complete energy payback from a DHe-3 fusion reactor utilizing lunar He-3 is ~80, providing ample incentive for commercial investment.

- Byproducts will be of great value to the resupply of a permanent lunar base and enhancement of space exploration.