A SYSTEMS ARCHITECTURE OF EXTRATERRESTRIAL PRODUCTION

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Abstract

The advance of space technology in general and the operation of space laboratories in near earth orbits in particular, have led to successful experiments in material processing under microgravity conditions. It also has become clear that the production of lunar oxygen would greatly improve the cost effectiveness of space transportation systems. Thus, it appears the time has come to define a frame-of-reference, including the functions and elements of extraterrestrial production activities which are expected to take place in future space stations and space factories. This report discusses potential product groups, identifies the functions to be performed and the system elements required. The interrelationships between both are illustrated. An attempt is made to show the expected evolutionary development of extraterrestrial production with the help of contextual diagrams and scenarios. This report contains 10 pages, 15 figures and 16 references.

1. Introduction

"Extraterrestrial Production (EP)" is a new activity made possible by the development in space technology during the last decade. With the introduction of manned space laboratories in the seventies, a series of experiments has begun which now makes it possible to plan seriously the processing of information, material and energy on a large scale commercial base.

The commercial aspects of space technology have begun in 1965 with the operation of the first commercial communication satellite. If the term EP is defined in such a way that it includes the production, conversion and distribution of information, energy and material products then 1965 was the initial milestone of this activity. The last two decades have seen an explosive development of information collecting and -distributing spacecraft, but only modest activities have been developed in the area of "space processing" of material products. This type of activity is expected to grow rapidly in the next decades with the establishment and operation of permanent space stations in East and West. Therefore, it appears that now is the time to attack the "extraterrestrial production" issue from the systems approach viewpoint and establish a "frame-of-reference" into which individual activities and projects can be integrated. To establish a draft for such a "frame-of-reference" is the purpose of this report. In this context we have to deal with:

1. Product groups
   to be processed outside the earth environment
2. Functions
   to be performed during extraterrestrial production
3. Subsystems and elements
   required for extraterrestrial production
4. Locations
   of activities and facilities in extraterrestrial space.

Fig. 1 System organisational dimensions.

Secondly, we have to define the boundaries of our system and to identify the fields of activities within EP. Figure 2 is an attempt to do this:

Function / Prod. Categ.	collecting converting	distributing
Material Products	- Products manufactured from terrestrial raw materials in extraterrestrial environment - Products manufactured from extraterrestrial raw materials in extraterrestrial environment - Acquisition and operation of extraterrestrial equipment and facilities = I	- Transportation of goods and passengers between Earth surface and the extraterrestrial facilities and from there to the individual customers by means of space transportation systems = II
Energy	- Conversion of solar energy into electrical or thermal process-energy at extraterrestrial locations by means of photo-voltaic or thermodynamical processes = III	- Transportation of energy converted in extraterrestrial facilities to terrestrial and/or extraterrestr. customers by means of reflectors, and/or microwave or laser transmitters and receivers = IV

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Information	- Collection of information about the human being, the Earth, the solar system and interstellar space by means of sensors onboard of spacecraft = V	- Distribution of information among and between terrestrial and extraterrestrial users by means of communication satellites and proper ground facilities = VI

Fig. 2 Fields of activities within "Extraterrestrial Production".

Starting with these fields of activity, we can derive product categories and functional elements of EP which need to be detailed, a process to be carried out in the following chapters. Before we can do this we have to identify the locations where extraterrestrial production may take place (see Fig. 3).

I. Low Earth Orbit (about 400 km)
II. High Earth Orbit (about 36 000 km)
III. Earth - Moon Neutral Gravity Point L-1
IV. Lunar Orbit (about 100 km)
V. Lunar Surface
VI. Planetary Moons (e.g. PHOBOS)
VII. Planetary Surfaces (e.g. MARS)
VIII. Astroids in Interplanetary Space

Fig. 3 Locations of activities and facilities in extraterrestrial space

These potential locations will be activated in a logical sequence, beginning in near orbits about the Earth as the need arises and if the cost-effectiveness shows promise in comparison with other alternatives.

This evolutionary process can be illustrated in a contextual map, shown in Fig. 4, where the evolution of the space transportation systems is tied to the evolutionary process in space operations which has been initiated with the use of various space laboratories.

This evolutionary process as shown in Fig. 4 will last a long period of time; the individual steps included in this contextual map will cover the development till the middle of next century.

2. Potential Product Groups

Next, we have to identify the products of interest in a representative manner. The following is a list of typical product groups. Their market prospectives vs. time are shown in Figs 5 and 6.

In Low Earth Orbit:

- Sensor carrying satellites measuring the geophysical environment about the Earth;
- Sensor carrying satellites surveying the sky and and astronomical objects;
- Sensor carrying satellites surveying and mapping the Earth surface and Earth atmosphere;
- Sensor carrying satellites observing military objects;
- Space laboratories and -factories manufacturing biomedical substances and pharmaceutical products;

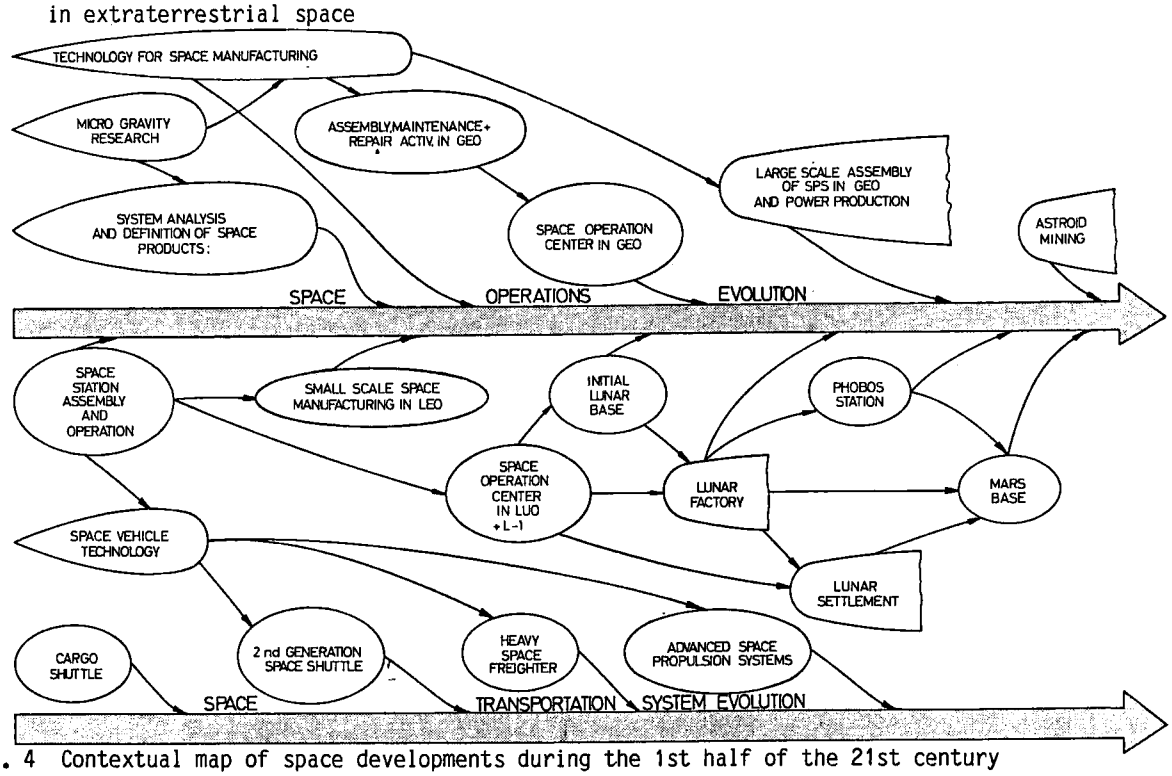

Fig. 4 Contextual map of space developments during the 1st half of the 21st century

- Space laboratories and factories manufacturing manufacturing semiconductor materials;
- Space factories manufacturing special glasses, materials and selected products of high cost per unit mass,
- Orbital launch facilities for servicing spacecraft.

In Geostationary and other high Earth orbits:

- Communication satellites and platforms for the global distribution of information;
- Geophysical satellites for permanent observation of the Earth atmosphere and the global environment;
- Satellites for permanent observation of military activities for purposes of early warning against surprise attacks;
- Space manufacturing facilities for producing large structures;
- Satellites for conversion of solar energy into electric energy for consumption on the Earth surface;
- Orbital Service Centers for storage of propellants and servicing orbital ferry vehicles;

On the surface of other celestial bodies:

- Laboratories and observatories for basic and applied research;
- Factories for the production of construction materials;
- Factories for the production of propellants;
- Power plants for the conversion of solar energy into electrical and process energy;
- Facilities for the production of nuclear fuels;
- Space ports for servicing and operating space transportation systems.

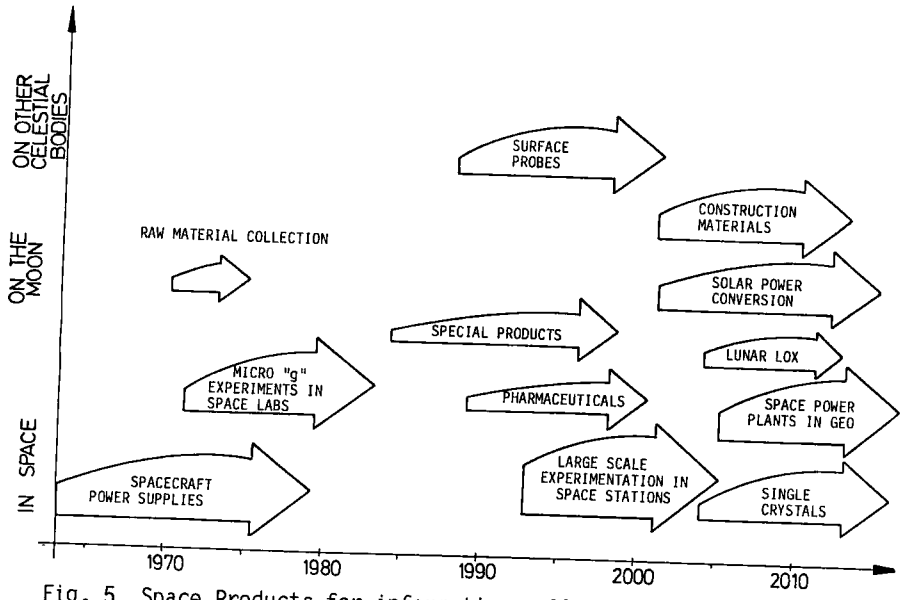

Fig. 5 Space Products for information collection and distribution.

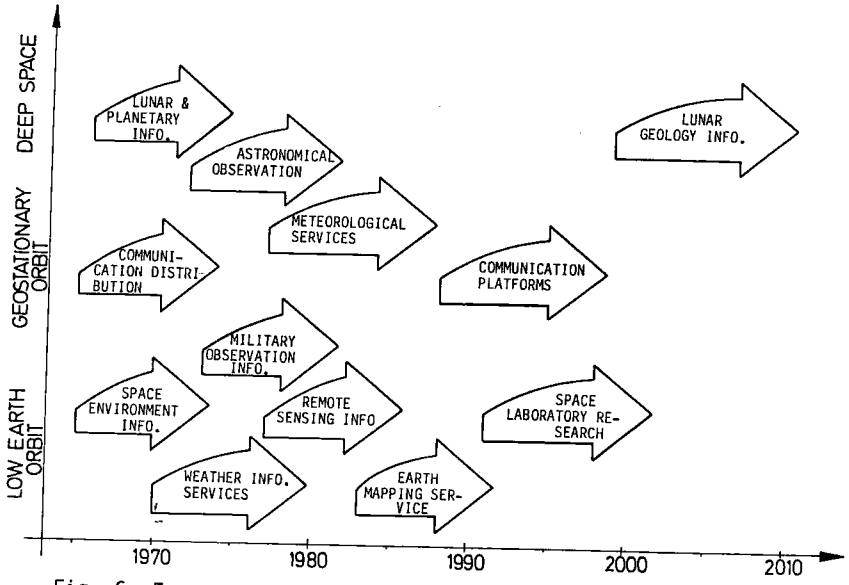

Fig. 6 Energy conversion and material processing.

3. Functions to be Performed within Extraterrestrial Production Activities

Next, we turn to the functions to be performed within this broad activity called "Extraterrestrial Production (EP)". This has to be detailed in such a way that we can derive from this list of functions the equipment and facilities required to carry them out. The functions within this system fall into the following four categories.

1. Production of raw materials
2. Production/manufacturing of end-products
3. Direct production support operations
4. Indirect production support activities

Fig. 7 Functions of Extraterrestrial Production.

We have now to subdivide these broad function categories into specific functions leading to individual pieces of hardware or work packages within a work-breakdown-structure to be developed. The following table is a first attempt for a detailed list of functions which will have to be supplemented in due course.

Not all of these functions will have to be performed with the same intensity at all extraterrestrial locations. Thus, it may be useful to indicate the distribution of these functions as they are presently anticipated to be required. This has been attempted in Fig. 9.

1. Production of raw materials:
   - 1-1: Mining of minerals
   - 1-2: Beneficiation of minerals
   - 1-3: Production of raw materials
   - 1-4: Production of propellants
   - 1-5: Production of metal-products (ingots, sheets, plates, wires, cables...)
   - 1-6: Production of non-metal raw products (fibers, crystals, solar cells...)

2. Production/manufacturing of end-products:
   - 2-1: Production of structural components and elements (bricks, pipes, panels, mats, brackets, beams, radiators...)
   - 2-2: Production of foodstuff (meats, vegetables, water, air...)
   - 2-3: Production of other products for own use (solar panels, filters, tools...)
   - 2-4: Production of other products for export (energy, Helium 3, pharmaceutica...)
   - 2-5: Assembly operations using produced and imported parts and components
   - 2-6: Services produced for export (maintenance and repair of space vehicles, tourism..; support of external research activities, rent of laboratories)

3. Direct production support operations:
   - 3-1: Supervision and control (of manufacturing processes, facilities and equipment including infrastructure)
   - 3-2: Maintenance and repair of facilities and equipment
   - 3-3: Extension of facilities
   - 3-4: Collecting and recycling (of trash a.scrap)
   - 3-5: Storage operations)

4. Indirect production support activities:
   - 4-1: Local transportation (within extraterrestrial complex)
   - 4-2: Power conversion, storage and distribution
   - 4-3: Habitation (life support, housing, recreation, health services...)
   - 4-4: On site training of personnel
   - 4-5: On site research activities in support of own needs (exploration, observation, experimentation)
   - 4-6: On site administration services (personnel management, financing, planning, legal aspects, public relation...)
   - 4-7: Logistics and space transportation

Fig. 8 List of detailed functions of Extraterrestrial Production

Fig. 9 see next page.

4. Subsystems and Elements of Extraterrestrial Production Complexes

We are now ready to identify the equipment and facilities which go along with the products and functions required. A tentative list is as follows:

PRODUCTION FACILITIES & EQUIPMENT

- A. Mining facilities and equipment
  - earth movers, beneficiation equipment, drills
- B. Mechanical processing shops
  - furnaces, mills, presses, NC machine tools
- C. Chemical processing facilities and equipment
  - for gases, liquids and solids
- D. Electrical/electronic shops
  - circuitry, solar cells
- E. Biological production facilities
  - food, flowers, animal farms
- F. Assembly facilities and equipment
  - tools, jigs, shops
- G. Transportation facilities
  - space and ground transportation systems and facilities
- H. Power infrastructur
  - conversion, storage and distribution facilities

INFRASTRUCTURE FACILITIES AND EQUIPMENT

- I. Maintenance and repair facilities
  - fixed and movable workshops, tools and equip.
- J. Research laboratories and facilities
  - contract facilities, product development, research supporting, selfsufficiency
- K. Habitats
  - living quarters, recreation facilities, space suits, hospital, training facilities
- L. Storage facilities
  - propellants, import products, export products, spares, trash
- M. Control facilities
  - communication, data storage, data processing, operational control equipment, software, administrative facilities

Fig. 10 Tentative list of EP subsystems.

FUNCTIONS OF EXTRATERRESTRIAL PRODUCTION: \ LOCATIONS:	in: LOW EARTH ORBITS	in: HIGH EARTH ORBITS	in: LUNAR CISLUNAR ORBITS AND L - 1	on: LUNAR SURFACE	of: PLANETARY & INTER-PLANETARY LOCATIONS
1-1 Mining of Minerals	-	-	-	XXX	XX
1-2 Beneficiation of Minerals	-	-	-	XX	XX
1-3 Prod.of Raw Materials & Feedstock	(X)	(X)	(X)	XXX	XXX
1-4 Production of Propellants	-	-	-	XXX	XX
1-5 Prod. of Metal Products	X	X	X	XXX	X
1-6 Prod. of Non-Metal Products	(X)	X	X	XXX	XX
2-1 Prod.of Structural Comp.& Elements	X	XX	X	XXX	XX
2-2 Production of Foodstuff	X	X	X	XX	XX
2-3 Prod.of other Products f.Own Use	-	-	-	XXX	X
2-4 Prod.of other Products f. Export	-	-	-	XXX	X
2-5 Assembly Operations	X	X	X	XX	XX
2-6 Services Produced for Export	X	X	X	XX	X
3-1 Supervision & Control	XXX	XXX	XX	XXX	XX
3-2 Maintenance & Repair	XXX	XXX	XX	XXX	XXX
3-3 Extension of Facilities	XXX	XXX	XX	XXX	XX
3-4 Collecting & Recycling	XX	XX	X	XXX	XX
3-5 Storage Operations	X	XXX	X	XXX	X
4-1 Local Transportation	X	XXX	X	XXX	XX
4-2 Power Conversion, Storage & Distrib.	XX	XXX	X	XXX	XX
4-3 Habitation	XX	XX	X	XXX	X
4-4 On Site Training of Personnel	X	X	X	XXX	X
4-5 On Site Research Activities	XX	X	X	XXX	XXX
4-6 On Site Administrative Services	(X)	X	(X)	XX	(X)
4-7 Logistics & Space Transportation	XX	XXX	X	XXX	XX

(X) negligible
X small quantities
XX medium quantities
XXX large quantities

Fig. 9 Anticipated distribution of individual EP functions at various locations.

Fig. 11 is a tentative list of subsystem elements.

A. Mining facility and equipment

1. Front-end-loader
2. Crusher
3. Sieves
4. Electromagnetic beneficiator
5. Drills

B. Mechanical shops

1. Furnaces
2. Mills
3. Presses
4. Universal welder
5. NC machine module
6. Wiring machines
7. Hand tools
8. Lifting equipment
9. Moving equipment

C. Chemical processing facility and equipment

1. Heaters and ovens
2. Acid leach tanks
3. Hydrolizer
4. Fractional distillation tower
5. Dissolving tanks
6. Hydrolyzing kiln
7. Drying kiln
8. Ion exchange separator
9. Reduction cell
10. Condenser
11. Platable metals separator
12. Heat exchanger
13. Conveyor belts
14. Lifting devices
15. Moving devices

D. Electrical/electronic shop

1. Mainframes
2. Electronic components
3. Computers
4. Measuring equipment
5. Wiring and cable machines
6. Generators, transformers
7. Electric motors, gears
8. Welding machines
9. Hand tools

E. Biological production and facilities

1. Greenhouses for food production
2. Small animal production facilities
3. Flower garden
4. Water recycling systems
5. Air recycling systems
6. Biological trash recycling system

F. Assembly facility and equipment

1. Beam builders
2. Weaving machines
3. Fixtures
4. Rigs
5. Lifting devices
6. Moving equipment

G. Transportation facilities and equipment

1. Conveyor belts
2. Earth moving equipment
3. Road building equipment
4. Pipelines
5. Cranes
6. Other lifting and handling equipment
7. Ground teleoperators
8. Small passenger cars
9. Long range passenger vehicles
10. Light trucks
11. Medium trucks
12. Heavy trucks
13. Mass drivers
14. Balloons and airplanes
15. Orbital maneuvering vehicles
16. Interorbital ferry vehicles
17. Ground launched rocket freighters
18. Ground launched passenger freighters
19. Propellant storage facilities
20. Launch and landing facilities

H. Power infrastructure

1. Solar farms on the ground
2. Solar power facilities in space
3. Energy reflectors in space
4. Nuclear reactors on the ground
5. Fuel cells
6. Power storage facilities
7. Power distribution system

I. Maintenance and repair facility

1. NC machine tools
2. Work benches
3. Welding machines
4. Hand tools

J. Research laboratories and facilities

1. Astronomical observatory
2. Biomedical laboratory
3. Physics laboratory
4. Geochemistry laboratory
5. Metallurgic laboratory

K. Habitats

1. Living quarters
2. Cafeteria
3. Health care center
4. Information center
5. Social center
6. Hobby shop
7. Clothing center
8. Personal supplies center

L. Storage facilities

1. Food and water storage
2. Waste collection systems
3. Imported production support materials
4. Export production storage
5. Spare part center

M. Control facilities

1. Communication center
2. Safety control center
3. Administrative offices
4. Production control center
5. Personnel management center
6. Transportation control center and motor pool
7. Systems and facility planning office

Fig. 11 Tentative list of subsystem elements.

We have now to correlate the functions and subsystemes. This is attempted in Fig. 12 which follows.

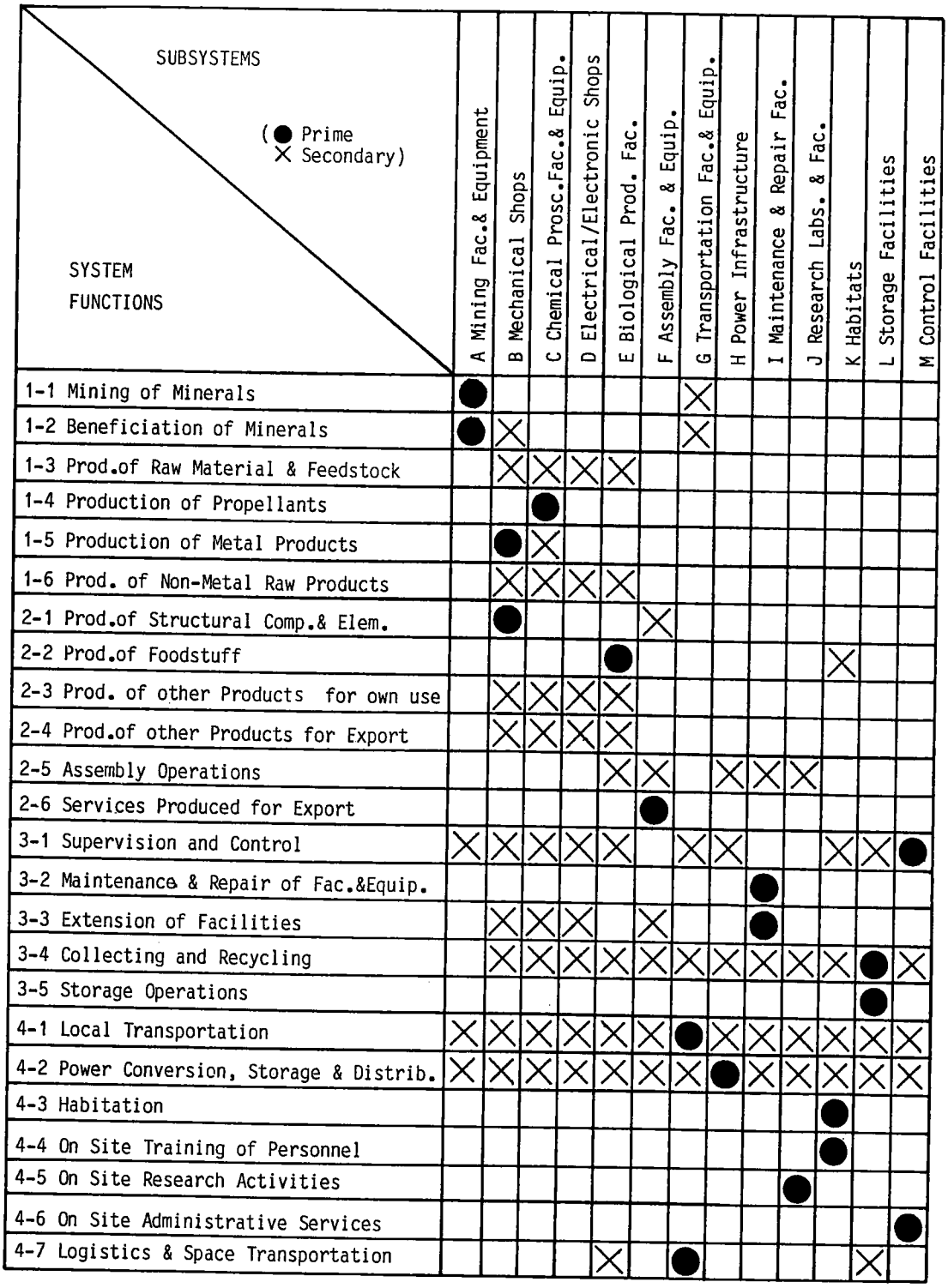

Fig. 12 Correlation of functions with subsystems.

The following figure is an example how the individual components of a subsystem can be allocated to various locations of EP.

TYPE OF TRANSPORTATION EQUIPMENT \ LOCATION OF EXTRATERRESTRIAL ACTIVITIES	Low Earth Orbits	High Earth Orbits	Lunar & Cislunar Orbits	Lunar Surface	Planetary & Interplanetary Activities
1. Conveyor belts	-	-	-	XX	X
2. Earth moving equipment	-	-	-	XX	X
3. Road building equipment	-	-	-	XX	X
4. Pipelines	X	X	X	XX	XX
5. Cranes	-	-	-	XX	X
6. Other lifting & handling equipment	X	X	X	XX	X
7. Ground teleoperators	-	-	-	XX	X
8. Small passenger cars	-	-	-	XX	XX
9. Long range passenger vehicles	-	-	-	XX	X
10. Light trucks	-	-	-	XX	X
11. Medium trucks	-	-	-	XX	XX
12. Heavy trucks	-	-	-	XX	X
13. Mass drivers	-	-	-	X	X
14. Ballons and airplanes	-	-	-	-	X
15. Orbital maneuvering vehicles	XX	XX	X	-	X
16. Interorbital ferry vehicles	XX	XX	XX	-	XX
17. Ground launches rocket freighters	XX	XXX	XXX	XXX	XXX
18. Ground launches passenger freighters	XX	X	X	X	X
19. Propellant storage facilities	XX	XX	XX	XXX	XX
20. Launch & landing facilities	XX	XX	XX	XXX	XX

Fig. 13 Types of transportation equipment required at various locations with Extraterrestrial Production activities.

5. Possible Development Scenario

To go further in developing this frame-of-reference one would now have to go down to the product level and, develop a functional work-breakdown structure that leads to individual research and development tasks to be performed on a specific time schedule. This schedule would result from a detailed PERT network study and presented in form of a bar-chart. This in turn would be the basis for determining the resources required to meet the product specifications on the desired schedule.

These individual product development plans have to be integrated into a comprehensive master plan for EP for each of the locations. This would allow to derive an overall research plan with the purpose to prepare the required technology in time.

This integrated plan is strongly dependent on the state-of-the-art in the field of space transportation systems. But this in turn is interdependent with the space market. Thus, we will probably end up with a systems model that allows us to simulate the process of EP as a function of time identifying the control variables of the system under consideration. It will take a few years to complete such an analysis and it will have to be up-dated continuously. But it is certainly not too early to get started.

Fortunately, in developing the evolutionary process of EP, we can start slowly with products of interest for EP activities in low Earth orbit. From there on we can add, step by step other products and other locations to keep the complexity of the system under control. This element is the key to a managable planning process in this area.

A long range scenario of Extraterrestrial Production has been developed (see Fig. 14) to assist in developing such a planning process and systems model. The stepwise process is clearly visible. If we limit ourselves to the development of EP in LEO, we can present an even more detailed scenario which is illustrated in Fig. 15. This could be the point of departure to go into more details.

6. Conclusions and Recommendations

At this point in time, the following conclusions may be permitted:

1. The initial experiment of extraterrestrial materials processing and production have been fairly successful and appear promising.

2. Several research institutions and commercial companies are actively engaged in developing equipment and products suitable for Extraterrestrial Production.

3. It will probably take another decade to come up with products and processes which will make Extraterrestrial Production a profit-making enterprise.

4. A key element for commercially viable Extraterrestrial Production is the development and availability of cost-effective space transportation systems which at this point in time appear to be the bottle-neck for further progress at a rapid rate.

5. In considering Extraterrestrial Production we may initially concentrate on the micro-gravity environment in near Earth space, but should not neglect the potential of geostationary orbits, orbits about the Moon and the lunar surface with its 1/6 "g", vacuum and its vast mineral resources.

6. Decisions which products should be produced where and when in extraterrestrial space with an advantage cannot be taken without an extensive systems analysis. This analysis must be done by simulating the entire process as part of the space system over the product life cycle.

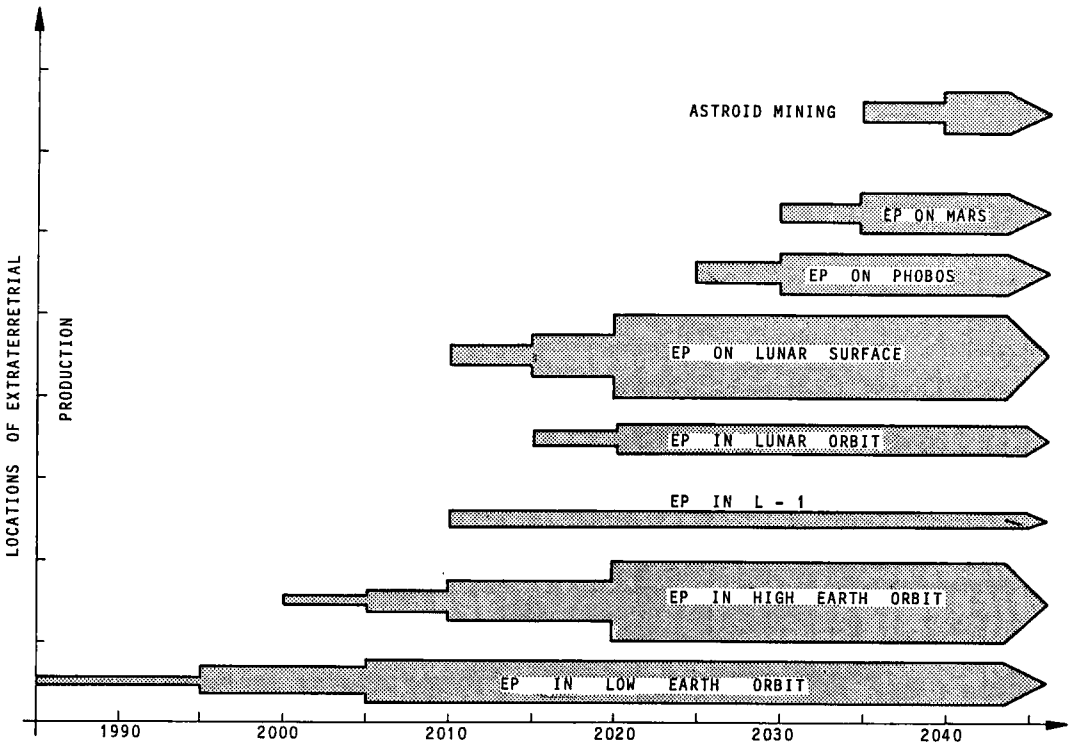

Fig. 14 Long range scenario of extraterrestrial production.

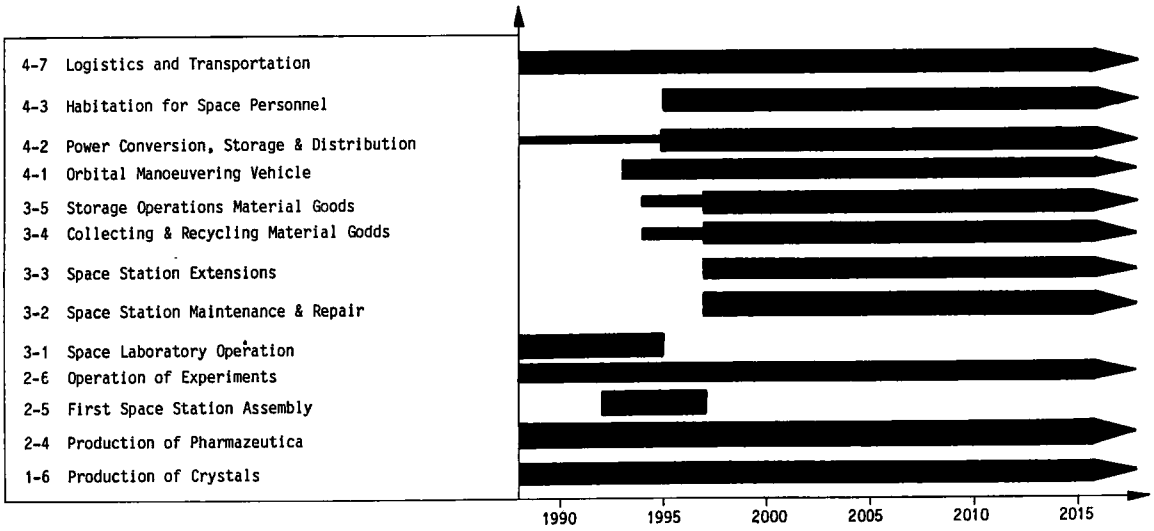

Fig. 15 Typical scenario of functions supporting extraterrestrial production activities in Low Earth Orbit.

Thus, it is recommended to continue aggressively experimental and theoretical studies in the field of Extraterrestrial Production to produce the relevant information required for individual product decisions. - A program plan for EP should be developed in due course which allows a phased development with increasing international participation. The logistics aspects of EP deserve special emphasis!

7. Summary of the Report

This report makes the attempt to structure an activity which has experienced increasing attention during the last decade of the space program "Extraterrestrial Production (EP)". A large number of experiments onboard of space laboratories in East and West have had promising results and indicate that under certain conditions advantage can be taken of the microgravity and vacuum environment of space.

This raises the question: Where do we go from here? Before this question can be answered, a "frame-of-reference" for this activity has to be developed which allows the assessment of the pros and cons of "Extraterrestrial Production" for individual products under consideration.

The primary dimensions of EP are: Products, functions, subsystems and elements, locations. These dimensions are discussed in some detail in this report and correlated where appropriate. The basic product categories are: Material products, energy and information. These can be collected, converted and distributed with the means space technology has to offer.

Eight locations where EP could take place are identified beginning with the low-near-Earth-orbit up to astroids in interplanetary space. A contextual maß is offered, illustrating the evolution of space activities relevant for EP (Fig. 4). Some twenty potential product groups suitable for EP which have been identified so far, are listed in chapter 2 and, their possible introduction with respect to the time dimension is shown in Figs. 5 and 6.

A tentative list of functions to be performed during EP is compiled in Figs. 7 and 8 and their distribution over locations indicated in Fig. 9. This list of functions is used to derive subsystems and elements required to carry them out (chapter 4). A matrix of system functions against subsystems illustrates the interrelationships between those two dimensions (Fig. 12). The subsystem G (Transportation equipment and facilities) is used as an example to indicate the allocations of the twenty elements listed to the individual locations of EP. The same process for the other subsystems has yet to be done.

These functional and organisational breakdowns are then structured in the form of bar charts as an evolutionary development process over the time axis in Figs. 14 and 15, thus, producing a long range scenario of EP and a more detailed scenario of the possible development in near Earth orbit. These are now ready for examination and refinement.

The conclusions are positive and encouraging in nature. It is noted that the rate of progress in the development of Extraterrestrial Production activities is strongly dependent on the cost-effectiveness of the space logistics system, presently the bottleneck in space development.

It is also pointed out that more experimental and theoretical work has to be accomplished before decisions can be made which products should be produced where and when in extraterrestrial space. Among the tools required for this assessment is the simulation of anticipated production processes within an overall life cycle simulation model. It is not too early to develop such models which will allow a better determination of the risks involved to enter such enterprises. It must be shown to the decision-maker that the pros outweight by far the cons from the viewpoint of the people living on this planet which they want to keep habitable.

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