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## SELF-REPLICATING SYSTEMS — A SYSTEMS ENGINEERING APPROACH


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16. ABSTRACT

This study develops a first approach to conceptualize self-replicating systems from past and present abstract theories. The engineering elements of Self-Replicating Systems are defined in terms of a basic reference system. A number of options are investigated. The growth characteristics and their problems are analyzed, the mathematics of various exponential growth options are outlined, and the problems of universal parts production and systems closure are discussed. Selected areas of further study are defined and a 20-year development and demonstration program is presented.

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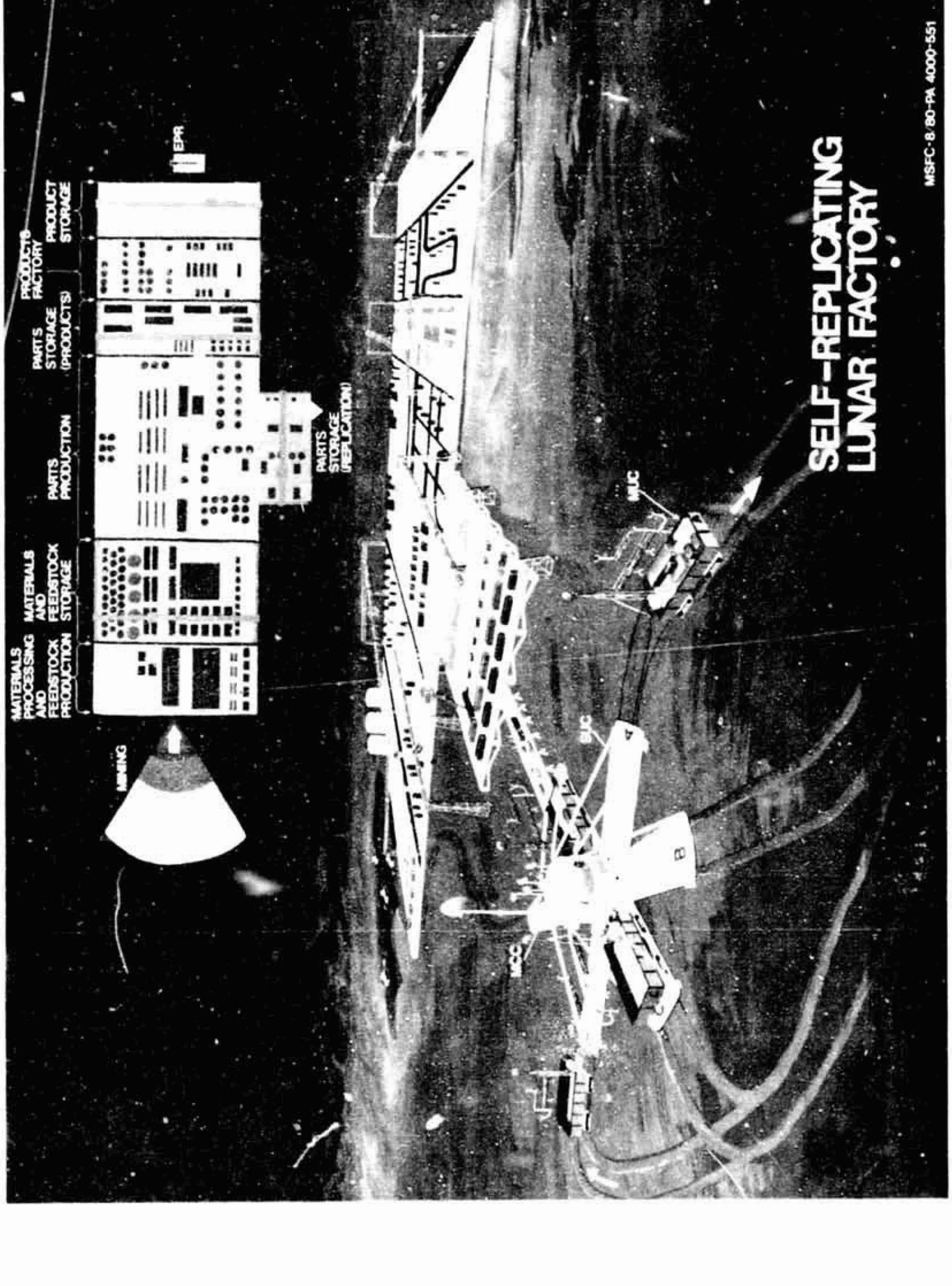
# PREFACE

In 1979 the concept of self-replicating systems was proposed to NASA. Its possible application for future space missions was discussed by the NASA Administrator and others within and outside the Agency. The very limited applicable literature, the highly theoretical and academic treatment of the subject so far, and the considerable complexity of such a system have resulted in this concept being unfamiliar to the engineering community.

This report originated from preparatory studies during 1979 and 1980 in anticipation of a 1980 Summer Study Workshop on "Automation Mission/Technology Feasibility" directed at future NASA mission opportunities with special consideration of self-replicating or growth systems.

This report presents a study to develop concepts of self-replicating systems that can be addressed in technical terms and, thus, generate an understanding of the composition and function of these systems. This objective has been achieved to a limited degree here because only the outermost layers of problems have been uncovered exposing numerous, yet uncharted, aspects. The results of this study phase, however, appear quite interesting and are submitted for helpful comments. NASA has no current plans to pursue a development program on self-replicating systems.


MINING
MATERIALS PROCESSING AND FEEDSTOCK PRODUCTION
MATERIALS AND FEEDSTOCK STORAGE
PARTS PRODUCTION
PARTS STORAGE (REPLICATION)
PARTS STORAGE (PRODUCTS)
PRODUCTS FACTORY
PRODUCT STORAGE
EPR
MUC
SUC
MCC
SELF-REPLICATING LUNAR FACTORY
MSFC-8/80-PA 4000-551

TECHNICAL MEMORANDUM

# SELF-REPLICATING SYSTEMS – A SYSTEMS ENGINEERING APPROACH

## SUMMARY

In the late 1940's John von Neumann began to develop a theory of self-replicating automata. Others followed and completed and expanded on his theories. This study presents an effort to convert the symbolic abstractions of self-replicating automata into technical engineering concepts. The various elements of such a system are defined and their tasks described. A first concept of a universal constructor is presented, a device which can build any machine if provided with proper instructions. Its elements and their tasks are described. The problems of universal parts production and systems closure are discussed.

The problems of exponential growth of such a system are addressed and solutions are presented to the problem of crowding and future expansion. The interesting computational aspects of growth rates involving various recursive number sequences are outlined. Among the selected areas for further study are the problem of mutations and reliability. This study is a very first approach to a complex engineering problem. It is hoped that further study will provide sufficient understanding for a comprehensive engineering assessment.

# 1.0 INTRODUCTION

In the late 1940's John von Neumann [1] began to develop a theory of automata. His substantial and unique works covered a broad area from which one is of particular interest in this study. He formulated and partially answered a basic question: What kind of logical organization is sufficient for an automaton to be able to replicate itself? He addressed and resolved the two a priori arguments against the possibility of self-replication: (1) that it is natural to expect the constructing automaton to be more complex than the constructed one and, (2) that unreliable parts cannot build a reliable system. Von Neumann's work is quite theoretical and describes the complexities of his five models of self-replication. Others that followed him completed and expanded on his theories.

To the knowledge of the authors there is no documented effort available to transform the theory into concrete engineering terms and concepts. This study attempts a first approach to the complex subject of self-replication in terms of engineering concepts, converting the abstractions of theory into building blocks of technical systems and scenarios.

An engineering reference system is postulated here. The large number of options that appeared during the study was recognized; however all were disregarded except those of major magnitude and importance.

A self-replicating system (SRS) is an organization of system elements capable of producing exact replicas of itself who, in turn, will produce exact replicas of themselves. The total number of systems thus generated grows exponentially. The replication process uses materials or components from its environment and continues automatically until the process is terminated. The SRS includes one system element which is the production plant for the desired product.

SRS's are applicable if the following criteria are fulfilled:

Large number of identical items required

Otherwise very long production periods

Raw material or parts available on site

Space available for replication.

At the beginning a first, reasonably sized primary SRS would be placed in the desired area, the self-replication process would be initiated and continued until the desired production capacity has been reached.

This limited study attempts to investigate some aspe of SRS's with regard to engineering concepts and systems growth characteristics.

# 2.0 THE ANATOMY OF A SELF-REPLICATING SYSTEM

## 2.1 General

J. von Neumann considered five different ways by which self-replication of a system would be possible: The kinematic, the cellular, the neuron, the continuous, and the probabilistic machine. Information on the latter three machines remained fragmentary; the cellular automation approach appears to be only a basis for theoretical analysis rather than for conceptual engineering design, and no link could be established between this option and a concrete machine design.

This report, therefore, is based on the kinematic model. Two extreme versions are possible here: one, where each replicating system is autonomous and of general purpose capability and two, where specialized individual systems elements are replicated by a central facility and are located in groups. The system grows by increasing the number of individual system elements [2]. The self-replicating, general-purpose autonomous concept is described and conceptualized here because it seems to have the greatest survival chance, reliability and versatility toward unexpected events.

The anatomy of an SRS is defined by two end conditions: (1) the type and quantity of products required within a certain time and (2) the available material required for these products and for the SRS itself.

The basic system elements of an SRS are (Fig. 1 and Frontispiece):

Material Processing and Feedstock Production Plant (MP)

Materials Depot (MD)

Parts Production Plant (PP)

Parts Depot for Replication (PDR)

Parts Depot for Production (PDP)

Production Facility (PF)

Universal Constructor (UC)

Product Depot (PD)

Product Retrieval System (PRS)

End Product Assembly/Collection System (EPS)

Energy System (ES).

The Work Breakdown Structure (Table 1) lists all SRS system elements and systems recognized in this study. The general nature of these is briefly described as follows.

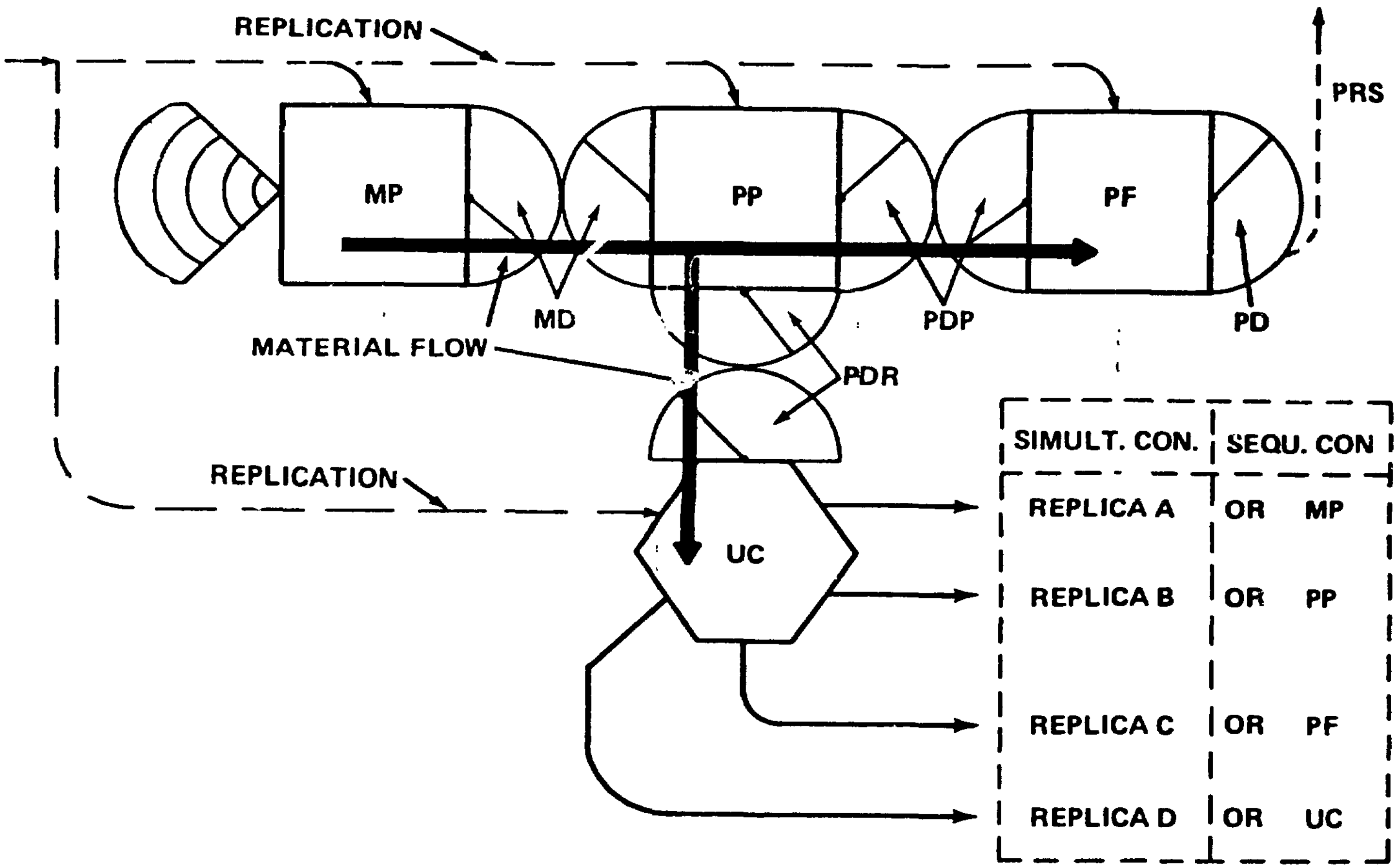



Figure 1. Schematic of a Self-Replication System.

# TABLE 1. WORK BREAKDOWN STRUCTURE

- **SELF REPLICATING SYSTEM**
  - **MINING AND MATERIALS PROCESSING SYSTEM**
    - MINING FACILITY
    - MATERIAL ANALYSIS AND SEPARATION FACILITY
    - MATERIAL TRANSPORT SYSTEMS
    - MATERIAL REFINING SYSTEMS
    - MATERIAL PROCESSING SYSTEMS
    - FEEDSTOCK TRANSPORT AND DISTRIBUTION SYSTEM
    - COMMAND CONTROL SYSTEMS
  - **MATERIALS DEPOT SYSTEM**
    - FEEDSTOCK TRANSPORT AND HANDLING SYSTEM
    - FEEDSTOCK RECOGNITION SYSTEM
    - FEEDSTOCK ACCOUNTING SYSTEM
    - COMMAND AND CONTROL SYSTEMS
  - **PARTS PRODUCTION SYSTEM**
    - FEEDSTOCK TRANSPORT AND HANDLING SYSTEM
    - FEEDSTOCK RECOGNITION SYSTEM
    - FEEDSTOCK DISTRIBUTION SYSTEM
    - PARTS PRODUCTION SYSTEMS
    - SUBASSEMBLY FACILITIES
    - PARTS AND SUBASSEMBLY TRANSPORT AND HANDLING SYSTEMS
    - WASTE RECYCLE LOOP SYSTEM
    - COMMAND AND CONTROL SYSTEMS
  - **PARTS DEPOTS SYSTEMS**
    - PARTS AND SUBASSEMBLY TRANSPORT AND HANDLING SYSTEMS
    - PARTS AND SUBASSEMBLY RECOGNITION SYSTEM
    - PARTS AND SUBASSEMBLY ACCOUNTING SYSTEM
    - COMMAND AND CONTROL SYSTEMS
  - **PRODUCTION FACILITY SYSTEM**
    - PARTS AND SUBASSEMBLY TRANSPORT AND HANDLING SYSTEM
    - DISTRIBUTION SYSTEM
    - PRODUCTION AND ASSEMBLY FACILITIES
    - TEST FACILITIES
    - WASTE RECYCLE LOOP SYSTEM
    - PRODUCT TRANSPORT AND HANDLING SYSTEMS
    - COMMAND AND CONTROL SYSTEMS
  - **UNIVERSAL CONSTRUCTOR SYSTEM**
    - STATIONARY UNIVERSAL CONSTRUCTOR
      - TURNTABLE
      - MASTER COMMAND AND CONTROL
      - INPUT GATE
      - OUTPUT GATES
      - GANTRY
      - CONVEYER
      - COMMAND RECEIVER
    - MOBILE UNIVERSAL CONSTRUCTOR
      - PARTS AND SUBASSEMBLY TRUCK
      - CONSTRUCTION AND ASSEMBLY SYSTEM
      - COMMAND AND CONTROL SYSTEMS
  - **PRODUCTS DEPOT SYSTEM**
    - PRODUCTS TRANSPORT AND HANDLING SYSTEM
    - PRODUCTS RECOGNITION SYSTEM
    - PRODUCTS ACCOUNTING SYSTEM
    - COMMAND AND CONTROL SYSTEMS
  - **PRODUCT RETRIEVAL SYSTEM**
    - PRODUCT HANDLING SYSTEM
    - PRODUCT TRANSPORT SYSTEM
    - COMMAND AND CONTROL SYSTEMS
  - **ENERGY SYSTEM**
    - CENTRAL
    - INDIVIDUAL
    - DISTRIBUTION
  - **END PRODUCT ASSEMBLY/COLLECTION SYSTEM**
    - PARTS AND SUBASSEMBLY TRANSPORT AND HANDLING SYSTEM
    - PARTS AND SUBASSEMBLY RECOGNITION SYSTEM
    - PARTS AND SUBASSEMBLY DISTRIBUTION SYSTEM
    - PRODUCTION AND ASSEMBLY SYSTEM
    - TEST FACILITY
    - COMMAND AND CONTROL SYSTEMS

## 2.2 Materials Processing and Feedstock Production Plant (MP (Fig. 2)

Here, raw materials are gathered by strip or deep mining, analysed, separated and processed into feedstock like sheets, bars, ingots, castings, and other. The processed feedstock is then layed out and stored in a materials depot (MD). The MP has a high degree of autonomy including self-maintenance and repair. It is linked to a central supervisory control system which is described later. The MP, therefore, consists of:

Mining Facility

Material Analysis and Separation Facility

Material Transport Systems

Material Refining Systems

Material Processing Systems

Feedstock Transport and Distribution System

Command and Control Systems.

## 2.3 Material Depot (MD)

The MP deposits the various feedstock categories according to a pre-determined plan such that the subsequent parts production may proceed in the most expedient way. It also forms a buffer during interruptions in the MP or PP. Therefore the MD consists of:

Feedstock Transport and Handling System

Feedstock Recognition System

Accounting System.

## 2.4 Parts Production Plant (PP) (Fig. 3)

The PP selects and transports feedstock from the MD and produces all parts required for SRS replication and the products. The finished parts are layed out and stored in either the Replication Parts Depot (PDR) or the Production Parts Depot (PDP). The PP is highly automated including material transport and distribution, production, control and subassembly operatio . The parts production covers the total requirements for the SRS replication and for the product production. The problems of universal parts production and systems closure are discussed in Section 3.0.

The PP, therefore, consists of:

Feedstock Transport and Handling System

Feedstock Recognition System

Feedstock Distribution System

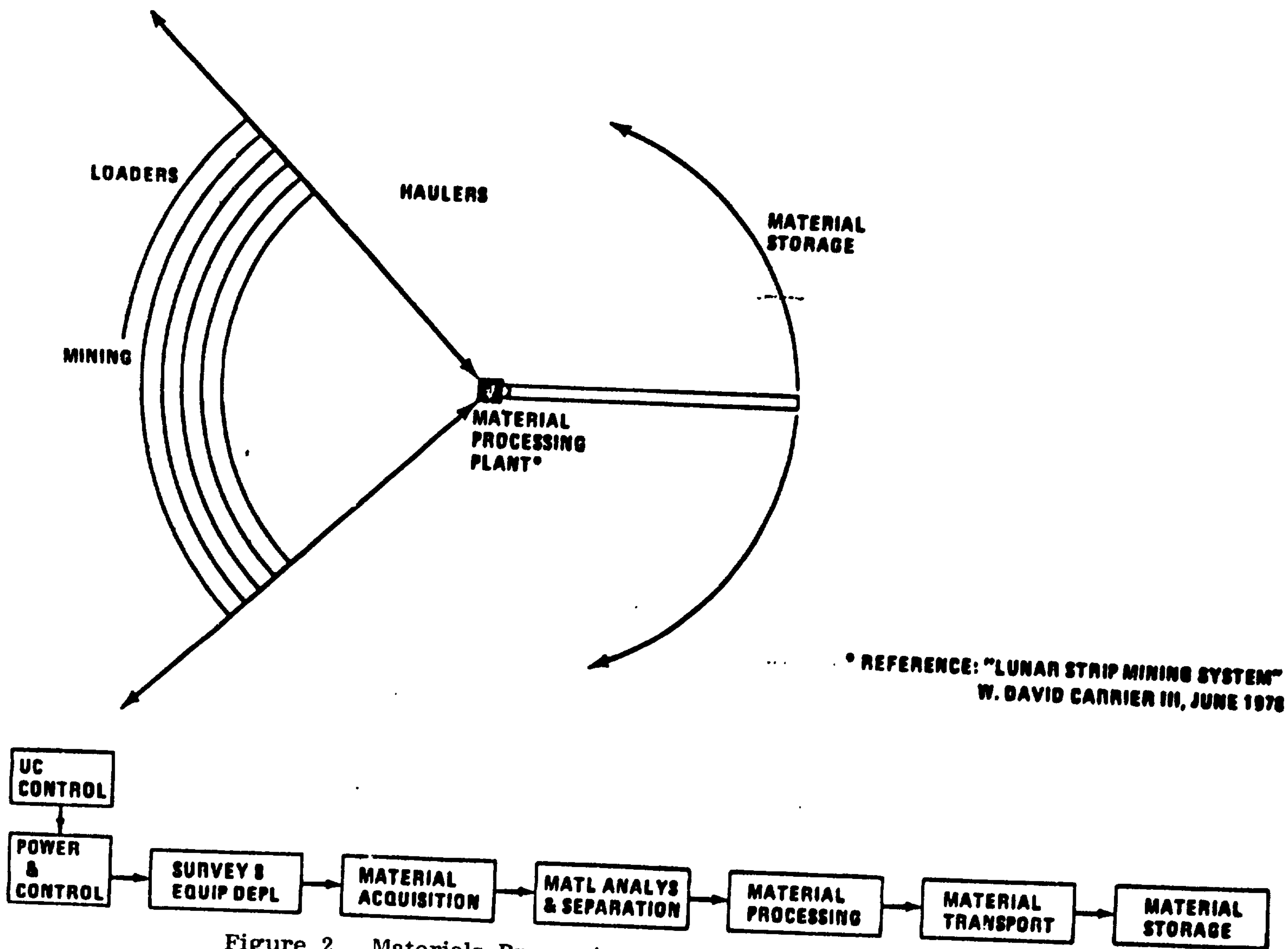



Figure 2. Materials Processing and Feedstock Production Plant (MP).

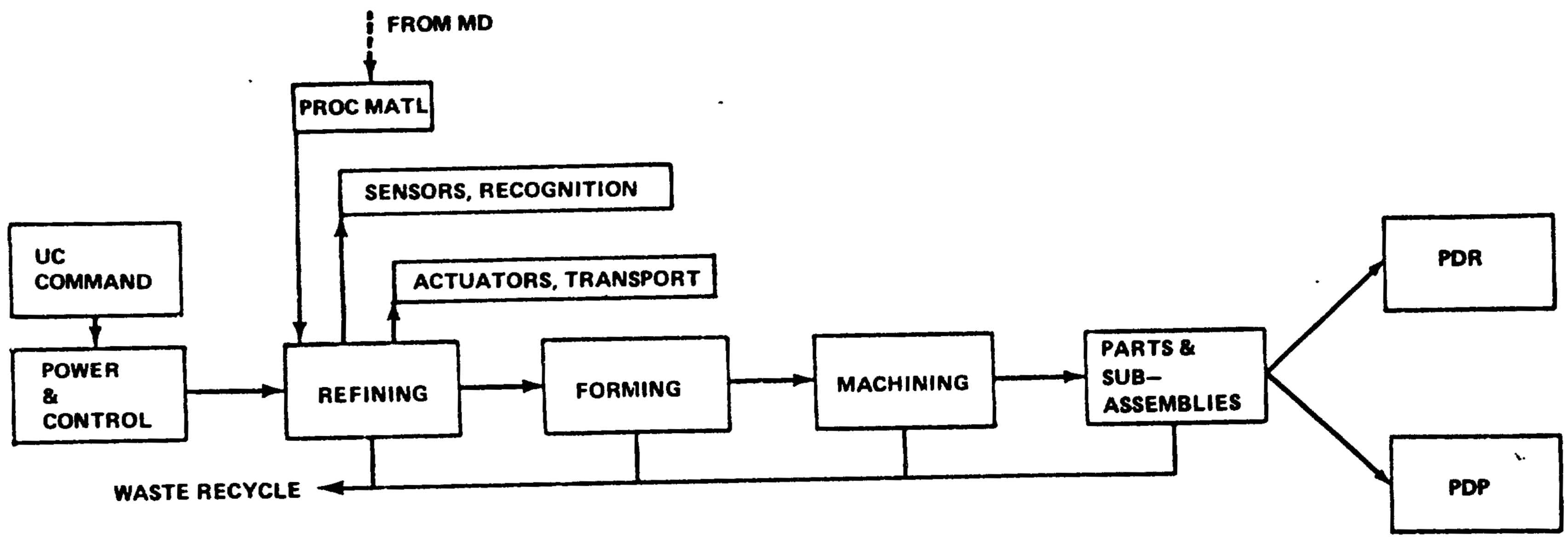



Figure 3. Parts Production (PP).

Parts Production Systems

Subassembly Facilities

Parts and Subassembly Transport and Handling Systems

Waste Recycle Loop System

Command and Control Systems.

## 2.5 Parts Depots

### 2.5.1 Replication Parts Depot (PDR)

All parts and subassemblies required for replication of complete SRS's are stored here in lots destined for specific facility construction. The layout is planned for the most expedient delivery to the construction sites by means described later. It also forms a buffer during interruptions in PP and UC.

### 2.5.2 Production Parts Depot (PDP)

Here, parts are stored exclusively for use in manufacturing the desired products in the PF. If this facility requires certain raw materials in addition to parts and subassemblies, these materials will have passed directly through the PP unchanged and stored in the PDR. The PDP also acts as a buffer during interruptions in PP and PF.

## 2.6 The Product Facility (PF) (Fig. 4)

This facility produces the desired products. Parts and subassemblies are picked up from the PDP, transported into the PF, and undergo specific manufacturing and production processes depending on the specified product desired. The finished products are stored in the PD to await pickup by the PRS system.

The PF, therefore, consists of:

Parts and Subassembly Transport and Handling System

Distribution System

Production and Assembly Facilities

Test Facilities

Waste Recycle Loop System

Product Transport and Handling Systems

Command and Control Systems.

Two options exist to construct the PF (Fig. 5). Economic considerations and construction schedule studies will decide which path to take. This study considered option (a) where an initial PF was delivered together with the initial SRS.

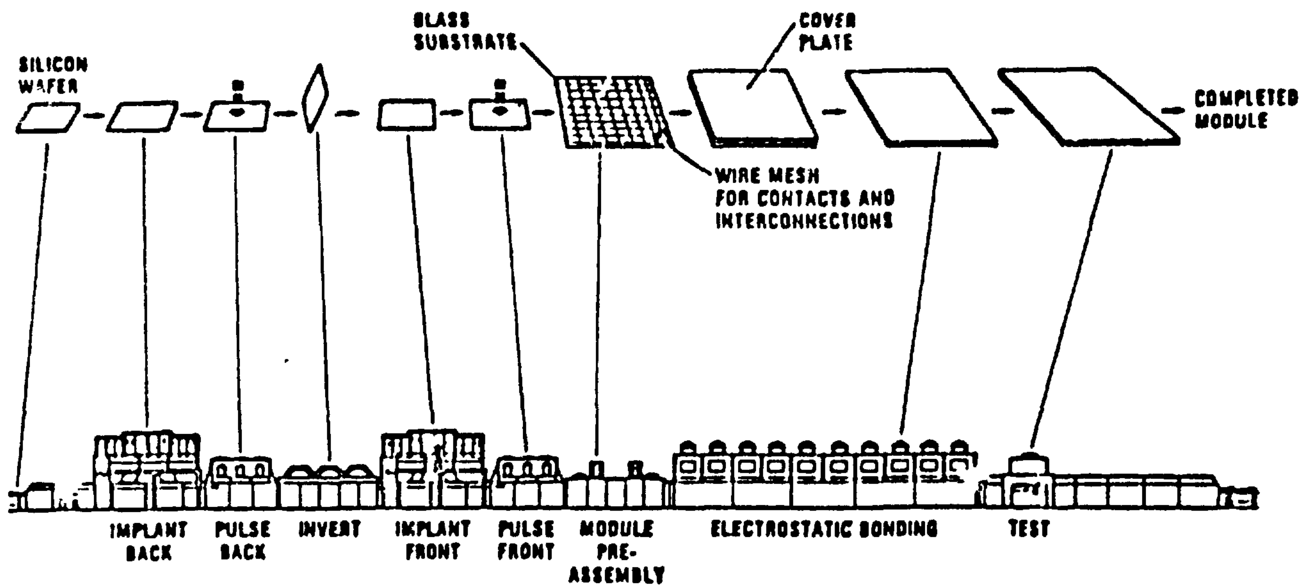



Figure 4. Production Facility (PF) (solar array) (automated process courtesy of Spire Corporation).

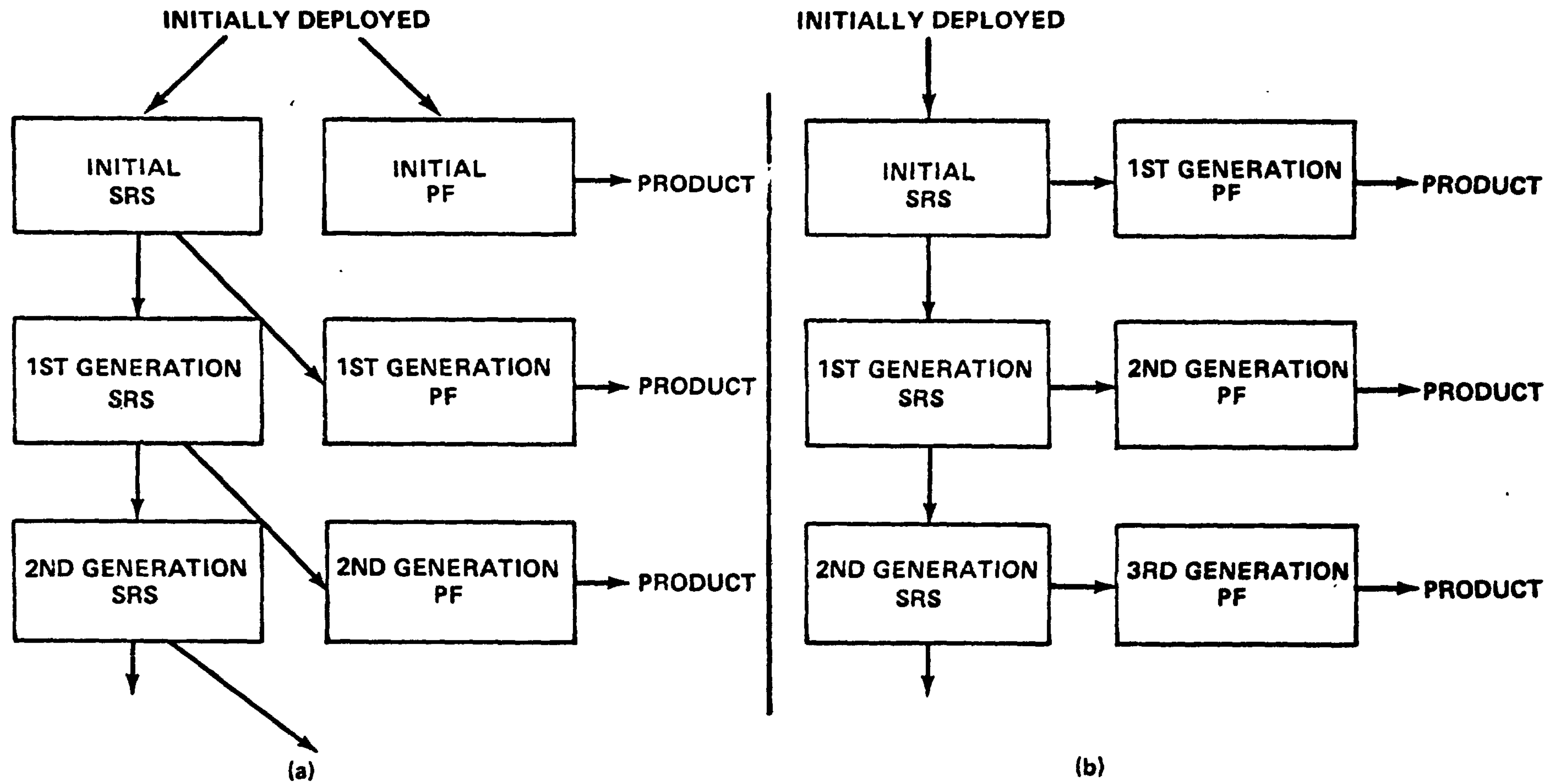



Figure 5. Options of product facility construction.

## 2.7 The Universal Constructor (UC) (See Frontispiece)

In principle, the UC is a system capable, upon instructions, of constructing any system. Here the purpose of the UC is to self-replicate a complete SRS a specified number of times in such a way that these replicas, in turn, construct replicas of themselves, and so on. The UC has the overall control and command function for its own SRS as well as for the replicas until control and command functions have been replicated and transferred to the replicas.

The command and control functions of the UC can be overridden by external means.

Unfortunately, von Neumann [1] did not find time before his death to leave a design for a CU, rather what is available are symbolic and abstract functions, proofs, and sequences. Therefore, the following is a first attempt to generate a plausible engineering concept that would carry out the self-replication functions. The UC has to perform the following tasks:

Receiving Parts and Subassemblies

Sorting Parts and Subassemblies

Loading Parts and Subassemblies

Transporting Parts and Subassemblies

Assembling and Constructing Systems

Installing Systems

Integrating Systems

Copying and Transferring Instructions

Testing Systems

Starting and Controlling Operations.

The UC consists of two major, separate elements:

a) The Stationary Universal Construction Unit (SUC) (Fig. 6).

b) Several Mobile Universal Construction Units (MUC) (Fig. 7).

The operational events taking place at the UC are as follows:

a) The gantry picks up parts and subassemblies and places them on the conveyor, arranged by subsystems.

b) The conveyor transfers the parts and subassemblies to the turntable where a MUC is parked.

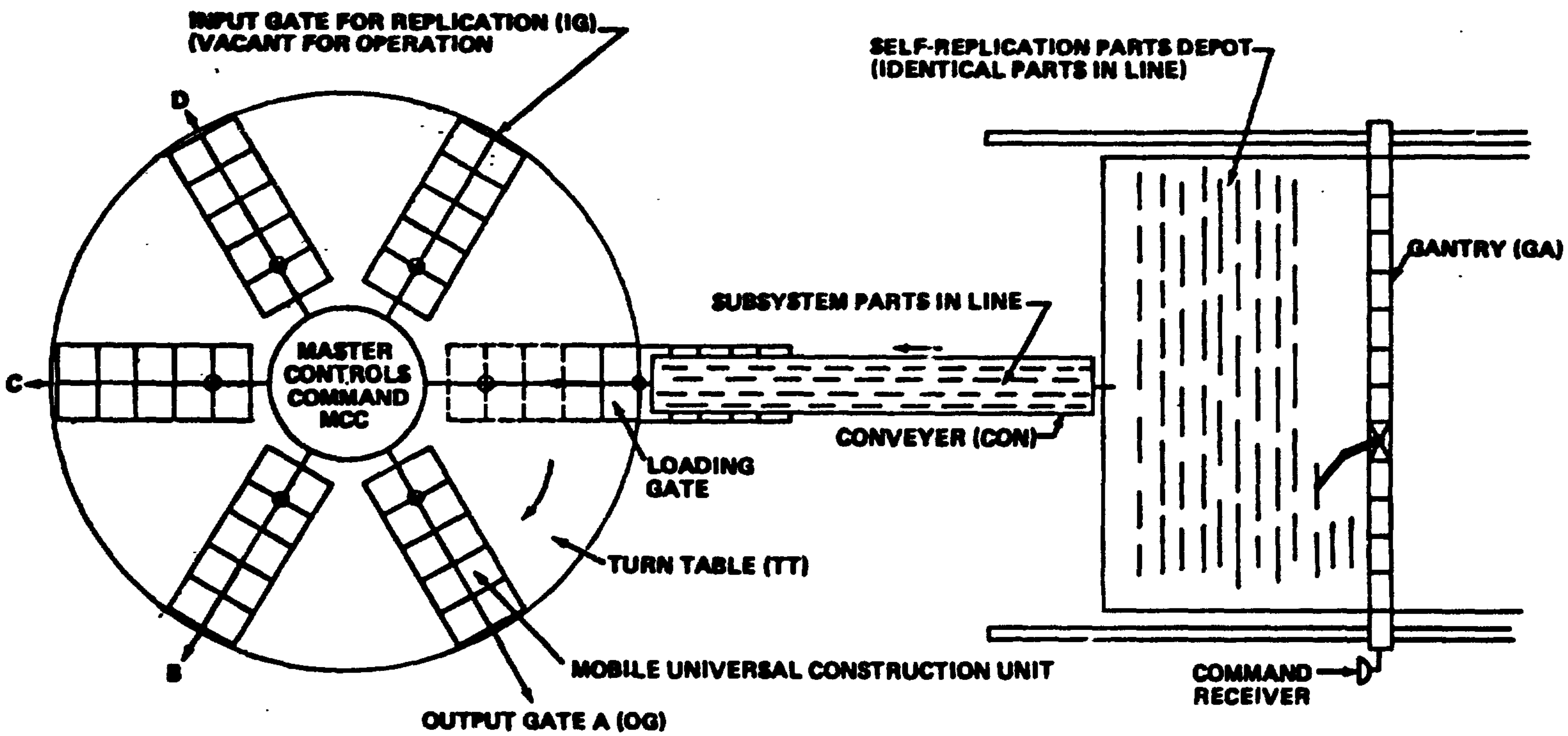



Figure 6. Stationary Universal Construction Unit (SUC).

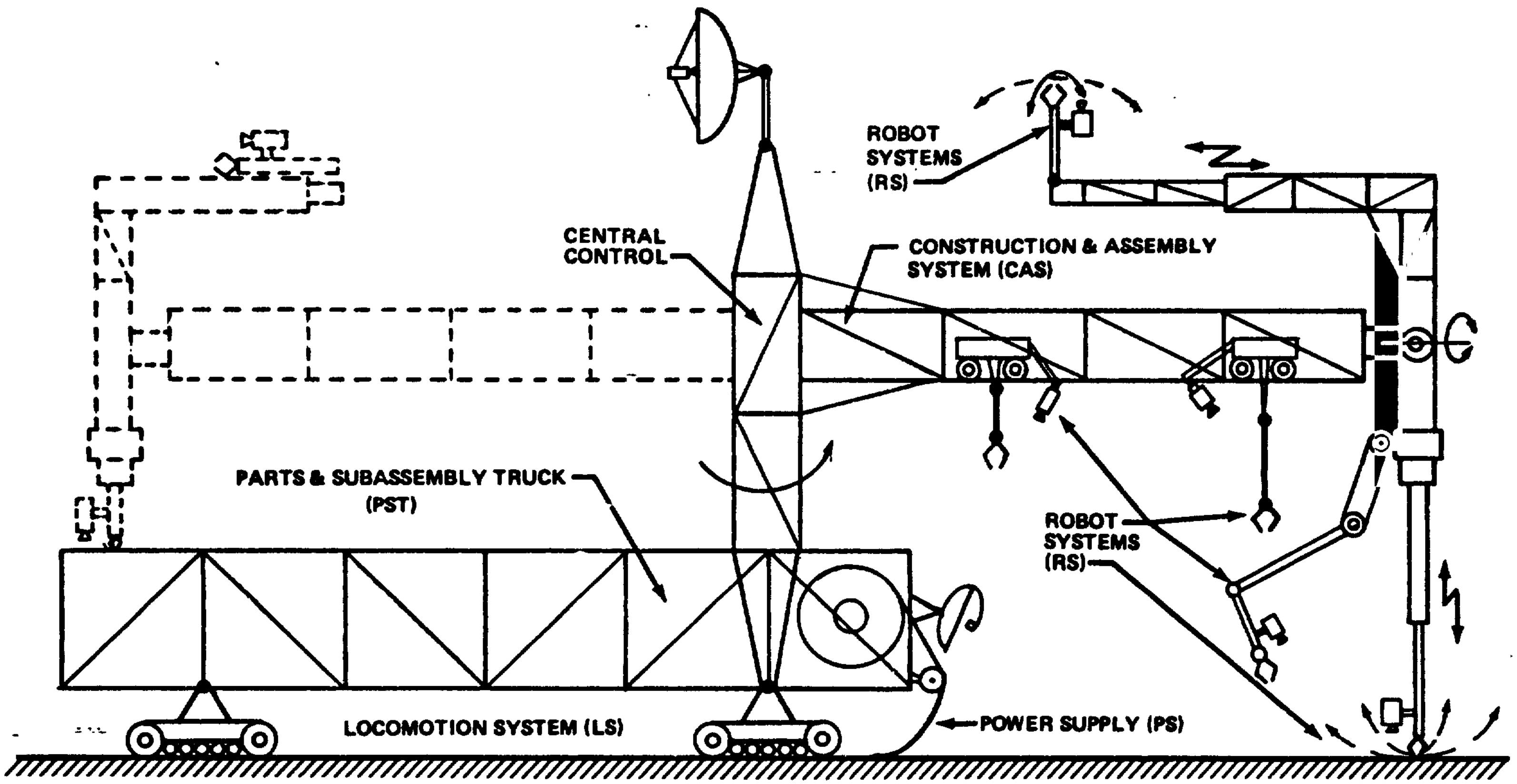


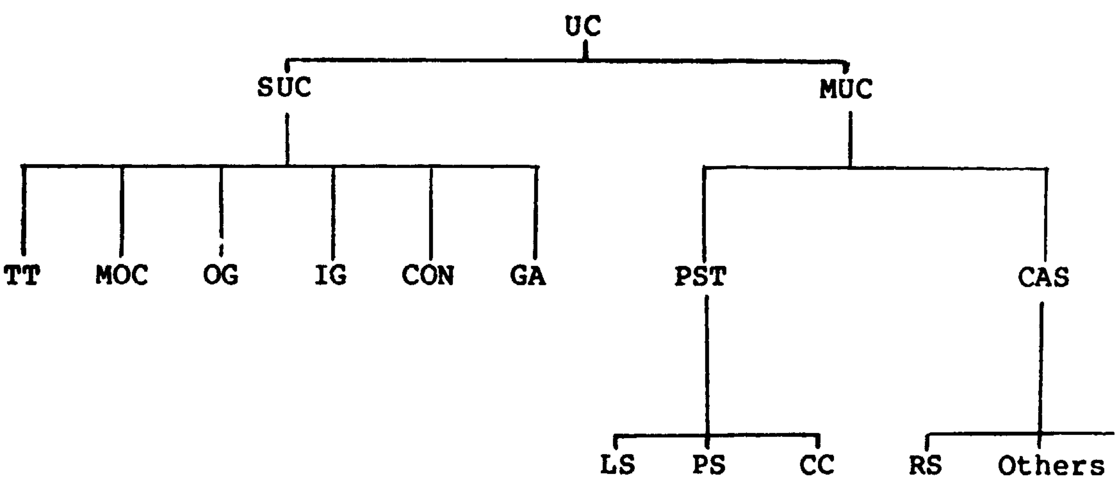

Figure 7. Mobile Universal Construction Unit (MUC).

c) The MUC's Construction and Assembly System (CAS) transfers the parts and subassemblies to the Parts and Subassembly Truck (PST).

d) The MUC departs to the construction site and begins construction. Continual commuting of the MUC back to the SUC will take place.

e) The turntable indexes for one sixth rotation and the next MUC is ready for loading.

The center of the SUC contains the central Master Control and Command System (MCC) which is programmed for supervising the total operation and which communicates with the peripheral controls of the MUC during the self-replication phase and with the replicated SUC during the transfer of command and control for the operation of the new unit. The MCC also supervises the operations of its own system elements from materials acquisition to product retrieval. In summary, the total composition of the UC is as follows:




2.8 Product Depot (PD)

The outputs of the PF are stored here, ready for retrieval. In case there are major hardware components for delivery to the EPS they are stacked in such a way to be picked up readily by the PRS. In case of pure elements (e.g. oxygen) storage will be in containers to be picked up and returned empty to the PF. The PD also serves as a buffer between varying output and retrieval rates.

2.9 Product Retrieval System (PRS)

The PRS collects the outputs of all units of an SRS Field and takes them the EPS. The dashed lines of Figure 13 show an example of this transport problem. This system's layout needs close consideration in the overall growth plan to arrive at an optimum PRS.

### 2.10 End Product Assembly/Collection System (EPS)

Depending on what end product is planned, the EPS may take many different forms. Potential end products are Photovoltaic Power Plant and Gaseous or Liquid Oxygen.

### 2.11 Initial Emplacement Requirements

The following primary systems must be placed at the selected site for SRS operations:

a) Materials Processing and Feedstock Production Plant (MP)

b) Parts Production Plant (PP)

c) Product Facility (PF). This is optional.

d) Universal Constructor (UC)

e) Segment of the Product Retrieval System (PRS) serving the primary system and each replica of that primary.

f) Segment of Energy System (ES) serving the primary and each of its replicas.

g) Segment of the End Product Assembly/Collection System in support of the primary and its replicas.

## 3.0 UNIVERSAL PARTS PRODUCTION AND SYSTEMS CLOSURE

### 3.1 Statement of Problem

Several workers in the area of SRS (Laing, Freitas, and others) have discussed a potential problem area which involves the PP of an SRS. This can be described as follows: If a primary system is to replicate itself it may only be able to produce a certain fraction of its number of parts, requiring a second machine to produce part of the remainder, and an undetermined number of machines to complete the replication. However, all these additional machines must then also be replicated, needing additional machines to do so and so on ad infinitum.

### 3.2 Approach to Problem Solution (Fig. 8)

We can gather evidence that this problem is solvab[illegible] we consider the finite characteristics of real machines. To do this w[illegible]ulate the problem as follows: "Can a set of machines produce all [illegible] elements?" The argument may be carried out as follows:

1) If all existing machines were disassembled into their individual parts there would obviously be a finite number of parts, many of them identical, and a large number would be of common categories like shafts. motors, wiring, etc. The only difference between the machines would be a different selection, arrangement and different dimensions of this finite number of parts.

2) A finite number of parts involves a finite number of machine operations, this number being less than the number of parts.

3) Therefore, the number of machines is finite and less than the number of operations.

This reasoning can then be generalized to say: "Every existing machine can be reduced to a finite set of machine elements, and there exists a finite set of machine operations."

We can therefore conclude that: "A finite set of machines can produce any machine element" (universal machine shop). In order to minimize the number of parts and of machine operations, however, a limited number of standard, common elements should be developed and machine operations should be limited as much as practical by substitution (e.g., die-casting instead of machining, grinding and finishing).

### 3.3 Extension of Approach

A similar reasoning may be applied to the materials processing and feedstock production:

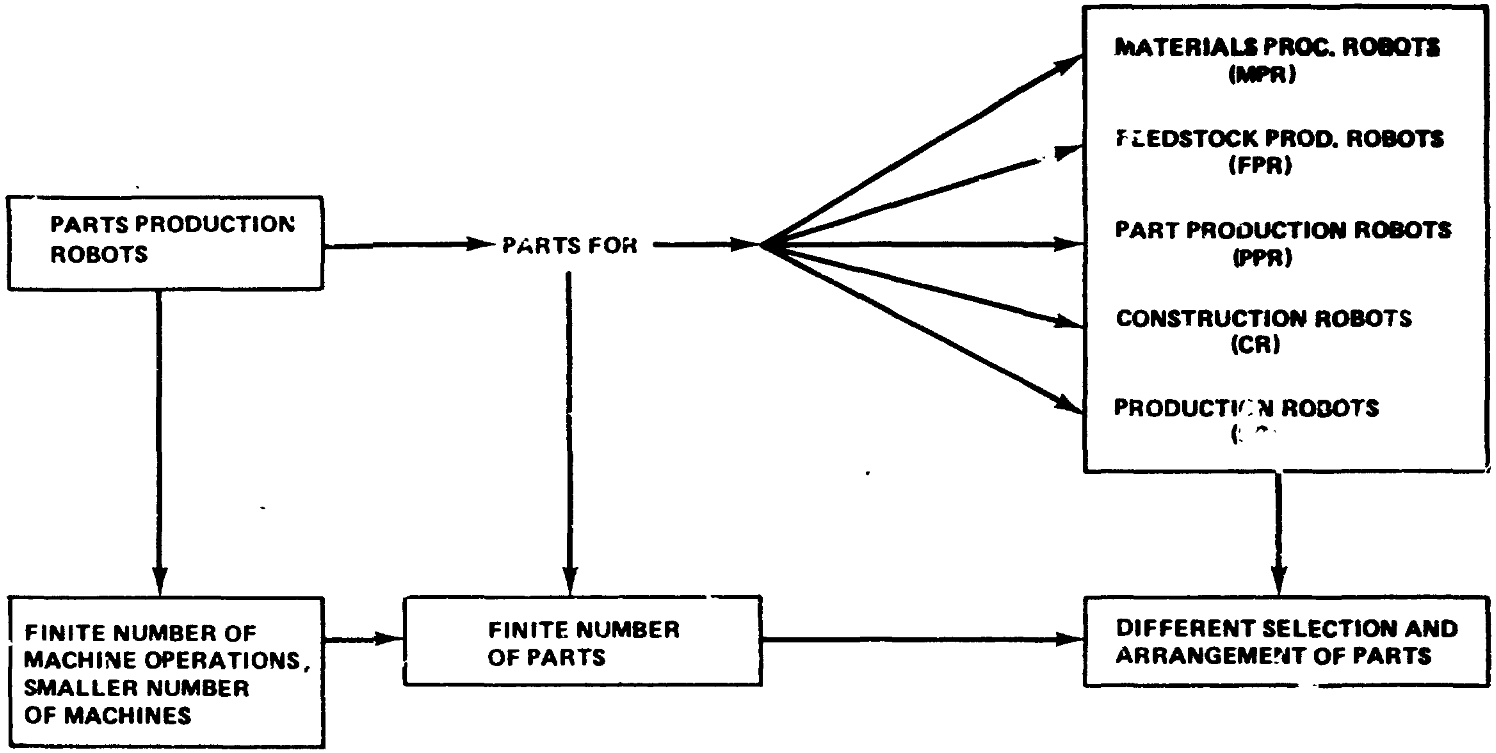



Figure 8. Closure of SRS parts production.

1) There exists a finite number of different materials anywhere.

2) There is a finite number of materials processes which is less than the number of materials because single processes result in various materials (e.g., silicon and oxygen).

3) There is a finite and rather limited number of feedstock requirements (e.g., bars, rods, ingots, plates, etc.).

4) The number of materials is much less than the number of parts.

5) Therefore, there is a finite and limited number of MPR's and FPR's required for an SRS.

## 4.0 ENERGY SYSTEMS (ES)

An SRS and more so an SRS field with a large number of SRS units will require a considerable quantity of energy to replicate and to produce. It is postulated that solar and nuclear energy are the only practical sources of that energy. Since a nuclear energy source cannot be replicated and a single source would be excessively massive (power requirements estimated in the gigawatt range) that leaves solar energy as the sole source.

The following daylight options for ES's can be considered:

a) Central photovoltaic with a ground cable network.

b) Distributed photovoltaic with local distribution system.

c) Individual photovoltaic.

d) Satellite Power System with a microwave or laser power transmission with options of a central, local, or individual receiver.

The following night options can be considered: MHD, thermionics, or turbogenerators using fuel generated with excess capacity during daytime. The fuel could be aluminum, calcium, or magnesium and oxygen. As a reference ES pending future tradeoff studies, a central silicon photovoltaic power station of 15 percent efficiency has been assumed. Since this ES may have output in the ten's of gigawatt range and, therefore, its size would be several tens of $km^2$ it must be outside the SRS field. A practical location seems to be near the End Product Assembly/Collection System (EPS) because a Production Parts Retrieval System (PRS) is already in existence (paragraph 2.9).

Each SRS will produce in the PF in line with its scheduled products a part of the ES equal to the energy needs of its replicas. This will be retrieved with the regular products by the PRS and assembled to the ES. The ES capacity, therefore, will grow with the demand during the self-replicating phase.

# 5.0 GROWTH CHARACTERISTICS OF SELF-REPLICATING SYSTEMS

## 5.1 General

The self-replicating process which proceeds from a single primary system to many hundreds of systems has to be carefully planned to reach the desired final capacity without running out of space and material.

There are possibly very large numbers of feasible growth patterns which allow selection to adapt to local area and material situations. For practical purposes certain constraints in the pattern selection must be applied if undue programming complexity is to be avoided.

The growth patterns investigated here are based on the following general groundrules:

a) Self-replication shall be sequential, one replica at a time by the primary system (Fig. 9A).

b) Each replica is constructed during a constant time interval t. This time interval is constant throughout the total system and is used as general time unit.

c) The number of replicas n of each "primary" system is a constant throughout the system. An exception is noted later on.

d) There is a pre-determined minimum spacing between adjacent replicas.

e) Production begins after the replication phase is turned off. No simultaneous replication and production except in option d.

## 5.2 Self-Replicating Options

The following notations are used:

n = number of replicas per primary.

m = number of generations until cutoff.

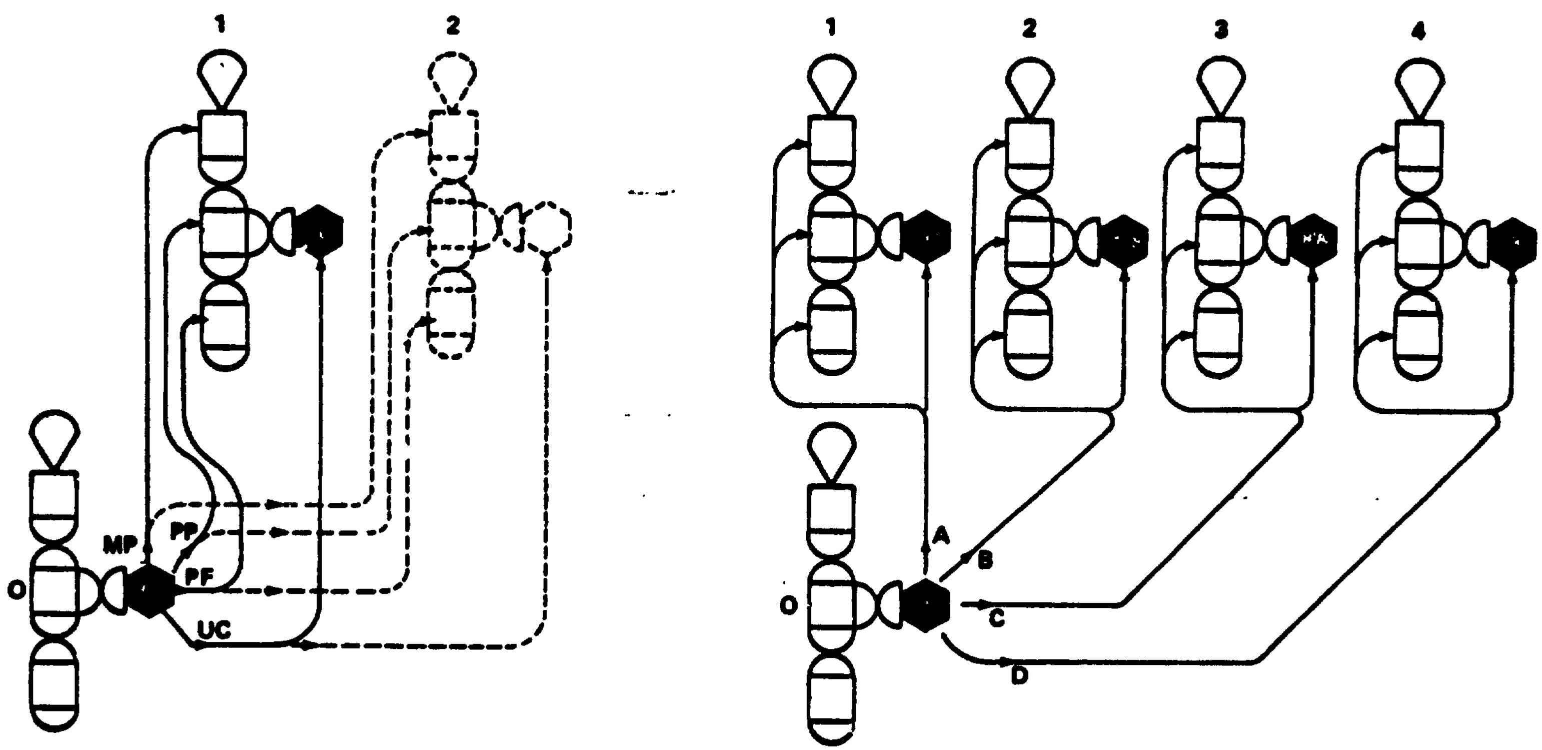
t = time required to replicate a system, the unit of time.

k = number of time interval (k = 1, 2, 3...)

$s_k$ = number of systems generated in the kth time interval.

T = total replication time between start and cutoff of the total system. This will always be a multiple of t to avoid unfinished systems.

S = total number of systems available at cutoff.




(A) SEQUENCIAL REPLICATION

(B) FOUR SIMULTANEOUS REPLICATIONS

Figure 9. Modes of Self-Replication.

There are four basic self-replication options available:

<u>Option a (Fig. 10)</u>

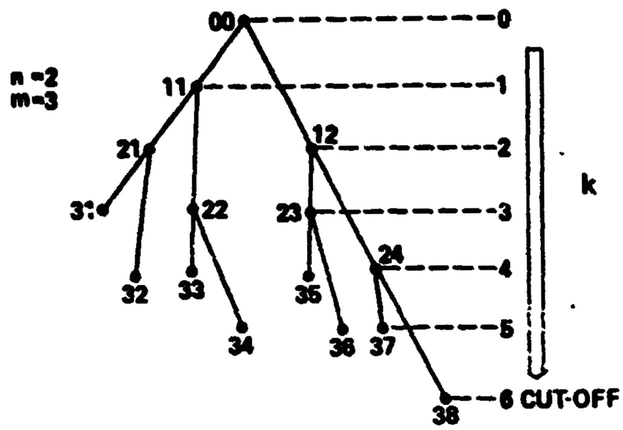



Figure 10. Option (a) S = 15.

Each unit produces a fixed number of replicas and begins production thereafter. Replication proceeds through a fixed number of generations for each branch of the system. We have

$$S = \frac{n^{m+1} - 1}{n - 1} \tag{1}$$

$$T = kt \tag{2}$$

$$k = nm \tag{3}$$

<u>Option b (Fig. 11)</u>

Like option a, a fixed number of replicas n is produced by each primary. However, replication continues throughout the system until cutoff at T. Due to the sequential replication, earlier branches will have produced more generations of replicas than later branches. We have:

$$s_i = s_{i-1} + s_{i-2} + \ldots + s_{i-n} \tag{4}$$

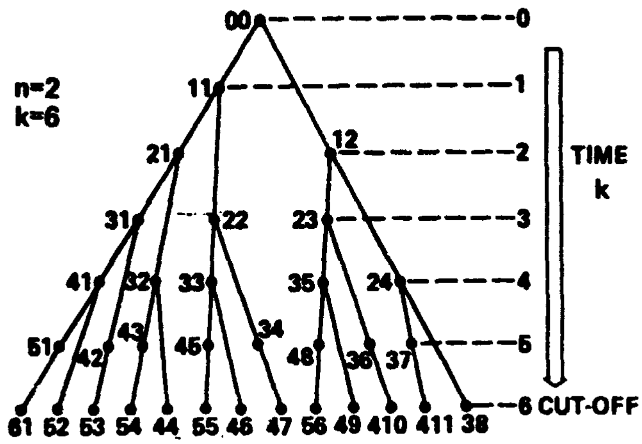



Figure 11. Option (b) S = 33.

The totals for each time interval form a recursive sequence of Fibonacci numbers where the number of replicated units at any time interval of length t is equal to the sum of the n preceding numbers of replicated units (See Section 6.0). Since there is always an original system 00 we have:

$$s_0 = 1 \quad . \tag{5}$$

At k = 1 the original has always produced the first replica (11); therefore,

$$s_1 = 1 \quad . \tag{6}$$

At k = 2 the original has always produced the second replica (12), and (11) has produced its first replica (21); therefore,

$$s_2 = 2 \quad . \tag{7}$$

From here on we construct the sequence according to equation (4). Similar to equation (2),

$$T = kt \qquad (8)$$

<u>Option c (Fig. 12)</u>

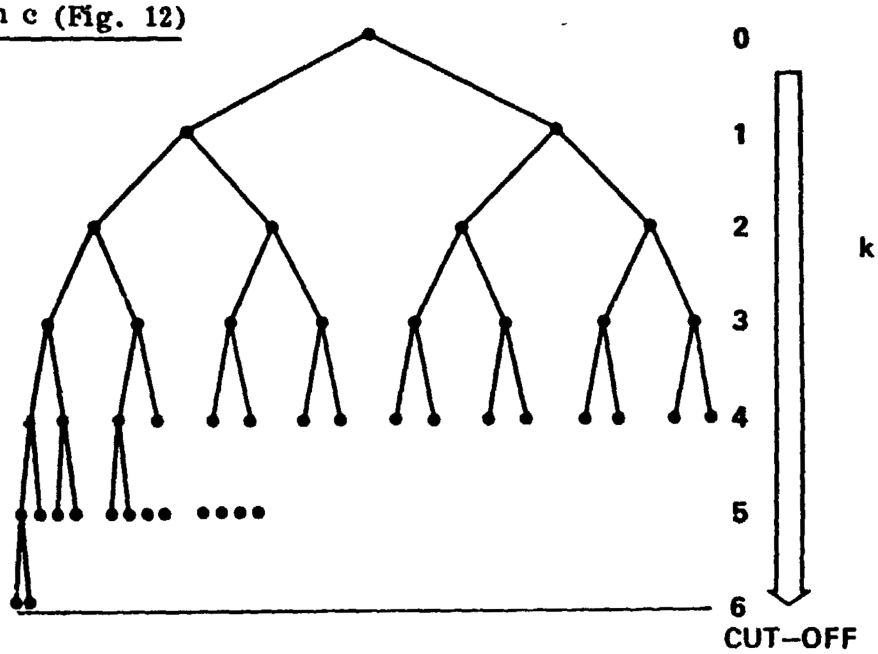



Figure 12. Option (c) S = 127.

By lifting one of the previous groundrules a SRS can produce its replicas simultaneously. Large mass flows and possible programming complexity are involved in this high production rate option.

Here we have:

$$S_T = \frac{n^{k+1} - 1}{n - 1} \text{ or } \frac{n^{m+1} - 1}{n - 1} \qquad (9)$$

$$S_k = n^k \qquad (10)$$

$$k = m \qquad (11)$$

## Option d

This option covers options a-c but with simultaneous replication and production rather than sequential (Fig. 9B).

The comparative growth rates of options a through c are given in Figure 13. A summary of the options is shown in Table 2.

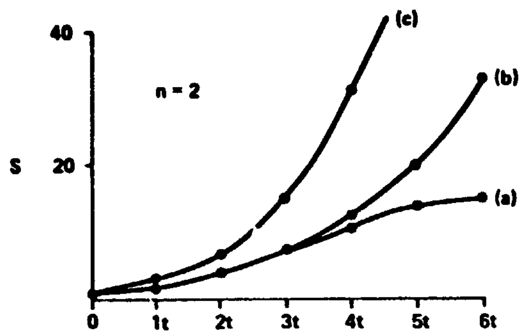



Figure 13. Growth rate comparison.

TABLE 2. SELF-REPLICATION OPTIONS

| Self-Replication Options | No. of Replicas | No. of Generations | Replication Timing | Production Versus Replication |
|---|---|---|---|---|
| a | Fixed | Fixed | Sequential | After |
| b | | Variable | | |
| c | | Fixed | Simultaneous | |
| d | Any of the above | | | Simultaneous |

### 5.3 Growth Plans for Self-Replication

A few examples of growth plans are discussed here. Figure 14 shows in some detail an SRS field with simultaneous construction of three replicas per primary over three generations resulting in a cutoff time of T = 9t (k = 9) and 40 units capacity.

The routes taken by the MUC's are shown by solid lines, the product retrieval routes taken by the PT's are indicated by dashed lines. Figure 15 shows a growth plan for an SRS field with sequential construction of replicas with n = 3 and T = 9t (k = 9) producing 326 units.

This type of growth pattern may be well suited for the production of different products in each cluster which then are assembled into a final product in the EPS. It is interesting to note that the number of units in each cluster is again a series of Fibonacci numbers. In the example shown in Figure 15, the clusters of the second generation (21 - 29) have the population

| Generation | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 |
|---|---|---|---|---|---|---|---|---|---|
| Population | 8 | 15 | 28 | 15 | 28 | 51 | 28 | 51 | 94 |

The number sequence is then:

(1) (2) (5) 8 15 28 51 94 . . .

which is the Fibonacci sequence for n = 3. Therefore, if one knows the population of the smallest cluster one may obtain the population of any other cluster of the same SRS Field. Obviously there is a large variety of growth plans possible; however, certain considerations are important, e.g.:

a) The best way to retrieve the products and transport them to the End Product Assembly/Collection System (EPS).

b) The best way to control and maintain growth up to the desired capacity.

c) The optimum relationship between programming complexity and space utilization.

### 5.4 Future Expansion of Self-Replicating Systems

Assume that the growth plan of an SRS field is layed out based on minimum desired distances between adjacent units constructed during the final time interval. If a later decision is made for an increased production capacity, a number of options are available:

a) The mass flow capacity for self-replication is expected to be greater than for production. The total capacity could be converted to production providing for ample growth.

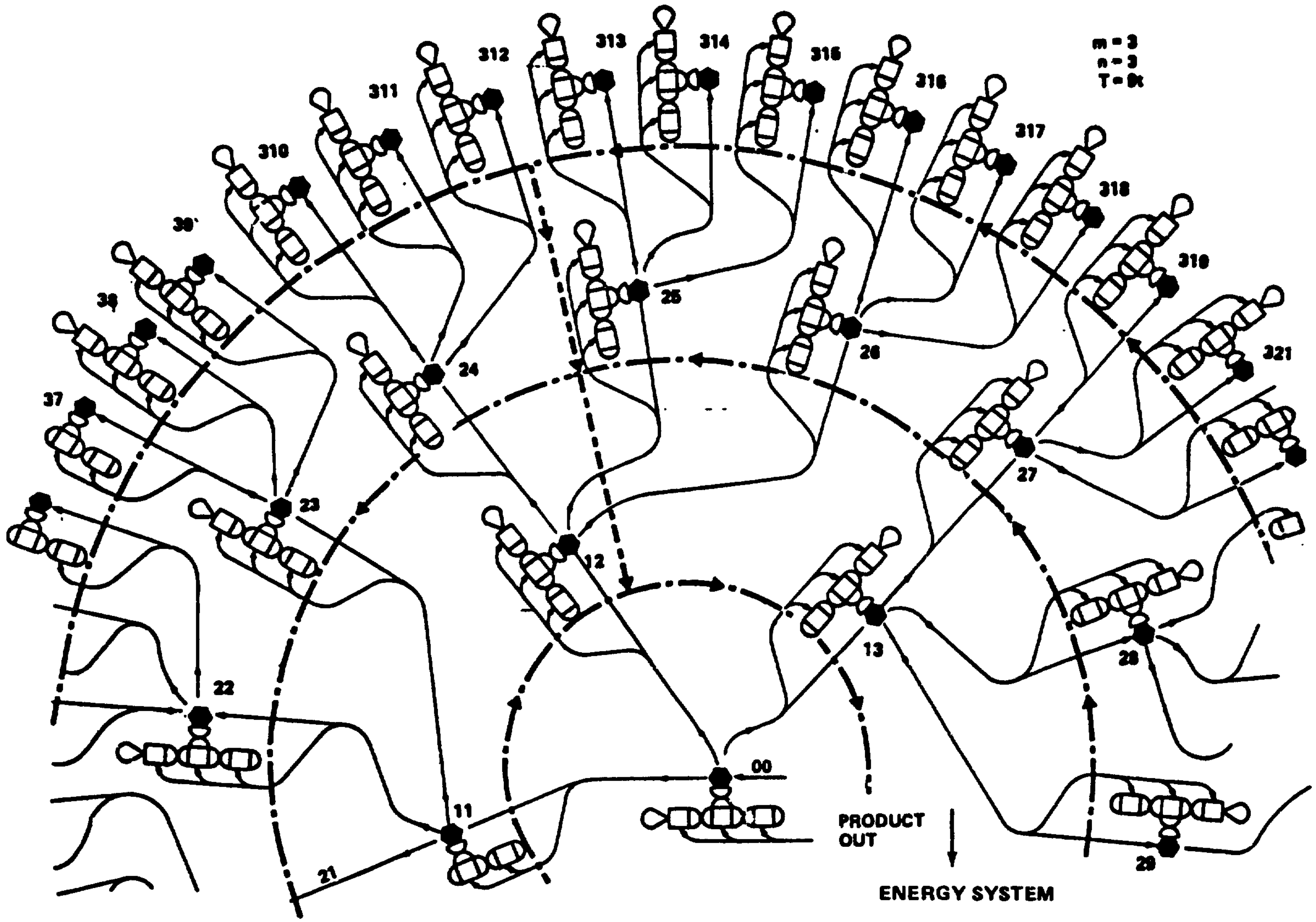



Figure 14. Growth plan (detail).

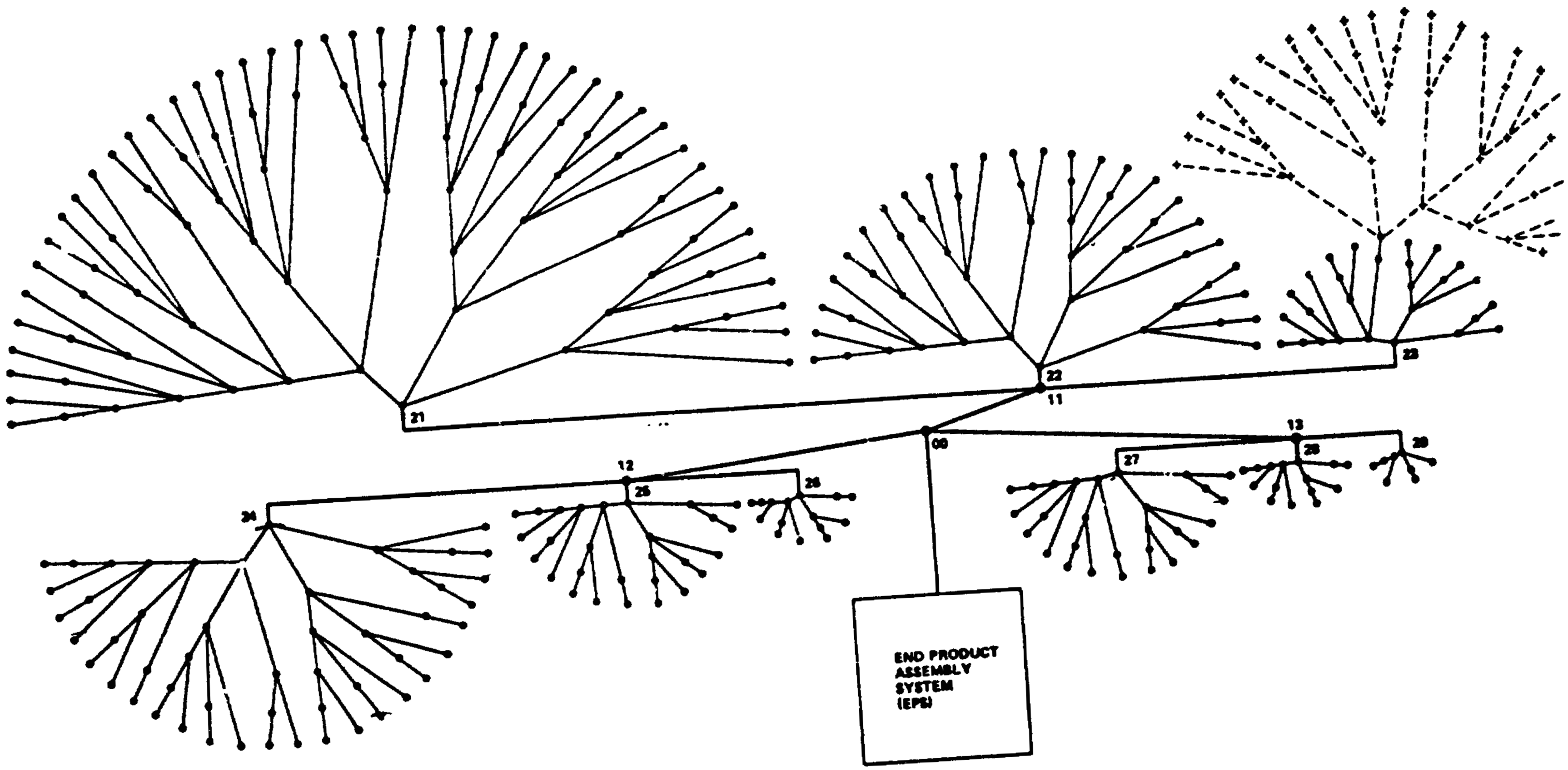



Figure 15. Growth plan (overview) (n = 3; T = 9t).

b) The use of "runners" appears practical. Selected SRS units of the final time interval could receive instructions to construct one or several single units in a suitable, radially outward direction (runners) and then return to standard instructions. Thus, the last unit at the end of the runner becomes the primary for a new SRS field (see dash lines in Figure 15).

### 5.5 Control and Command (CC)

A first cut at required CC between SRS elements is shown in Figure 16. The overall Master Command and Control System (MCC) of the UC is shown in the center operating its own SRS unit through individual communication links. These address the local CC system of individual SRS elements. These, in turn, communicate with each system within the elements.

MCC is also connected to the stationary and the fleet of Mobile Universal Construction Units (SUC and MUC's) which replicate the primary SRS above. A possible option becomes apparent from this figure: an all mobile UC could move from place to place and construct more than one replica. This would mean separation of operation and replication. This needs further investigation.

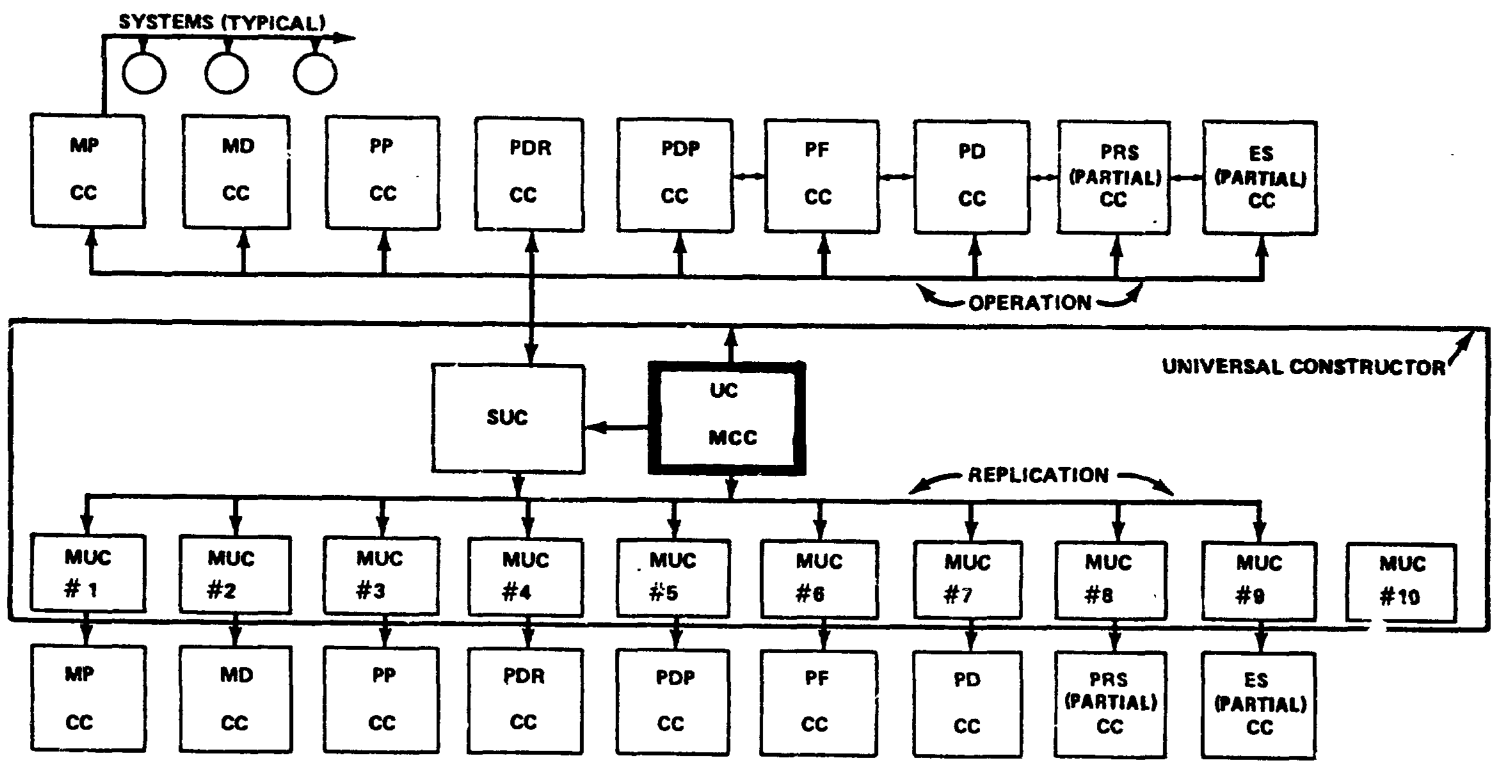



Figure 16. Control and command links between SRS elements.

# 6.0 COMPUTATIONAL ASPECTS OF SELF-REPLICATING SYSTEMS

This section addresses two cases, those referred to as Option a and Option b of the previous section. Several formulas will be derived and those most useful, it seems, are 17, 18, 19, 22 and 23. There are multitudes of novel relationships that one may discover hidden in replicating sequences [3].

We begin by looking at Option b where replication continues throughout the system until cutoff at time T = kt. To more clearly illustrate the methods used to derive the formulas we will concentrate on the case of two replications per primary, n = 2, and refer to Figure 10. We begin by noting the relationship which must exist between the number of replicas produced in each time interval. Any replica must have been produced during one of the previous time frames since each replica produces two offsprings, one in each of the two time frames immediately following its own construction. This means that the total number of replicas $s_i$ produced in the ith time interval equals that produced in the previous two, i.e.,

$$s_i = s_{i-1} + s_{i-2} \quad . \tag{12}$$

This recursion relation with $s_o = s_1 = 1$ gives precisely what is known as the Fibonacci numbers. One may compute the total number of replicas $S_k$ in k time intervals as follows. We rewrite the above equation $s_{i-2} = s_i - s_{i-1}$.

$$s_o = 1$$

$$s_1 = \cancel{s_3} - s_2$$

$$s_2 = \cancel{s_4} - \cancel{s_3}$$

$$\cdot$$
$$\cdot$$
$$\cdot$$

$$s_k = s_{k+2} - \cancel{s_{k+1}} \quad . \tag{13}$$

$$\overline{S_k = s_{k+2} - 1}$$

Since $s_2 = 2$ and for $n = 2$, the total number of replicas after k time periods is one less than that which would be produced during the second time period in the future or equivalently, using equation (13), we obtain one less than twice those of the present frame plus those of the last i.e.

$$S_k = 2 s_k + s_{k-1} - 1 \quad .$$

Instead of using equation (12) to generate the $s_k$, we may alternately find the number of replicas produced during the kth time period by adding the elements of Pascal's Triangle lying along a 22.5° line beginning on the kth line (Fig. 17):

$$s_k = \begin{cases} \sum_{i=0}^{j} \binom{j+i}{2i} & \text{for } k = 2j \text{ (even)} \\ \sum_{i=0}^{j} \binom{j+i+1}{2i+1} & \text{for } k = 2j+1 \text{ (odd)} \quad . \end{cases} \tag{14}$$

There are many approaches one may use to arrive at useful formulas. For example we note that the function $f(z) = 1/(1 - z - z^2)$ is a generating function for the $s_k$. That is

$$\frac{1}{1 - z - z^2} = \sum_{k=0}^{\infty} s_k z^k \quad . \tag{15}$$

Also f(z) is analytic in the complex variable sense with singularities only the simple poles at

$$p_1 = (-1 + \sqrt{5})/2 \text{ and } p_2 = -(1 + \sqrt{5})/2.$$

| $s_k$/m | 0 | 1 | 2 | 3 | . . . |
|---|---|---|---|---|---|
| $s_0$ | 1 | 1 | 1 | 1 | . . . |
| $s_1$ | 0 | 1 | 1 | 1 | |
| $s_2$ | 0 | 1 | 2 | 2 | |
| $s_3$ | 0 | 0 | 2 | 3 | |
| $s_4$ | 0 | 0 | 1 | 4 | |
| $s_5$ | 0 | 0 | 0 | 3 | |
| $s_6$ | 0 | 0 | 0 | 1 | |
| ⋮ | | | | | |

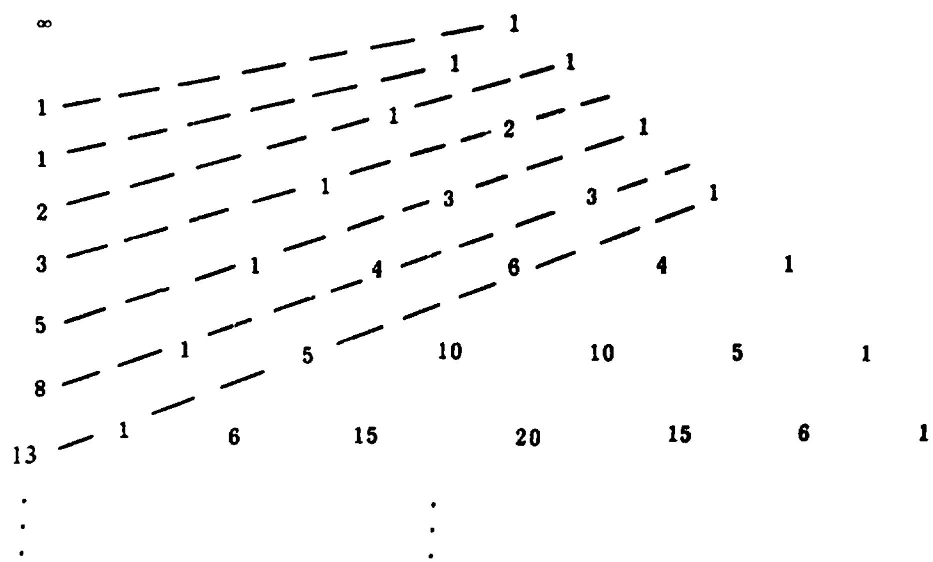



Figure 17. Replication (n = 2) and Pascal's Triangle.

Using Cauchy's integral theorem ꜝ Cauchy's residue theorem,

$$s_k = \frac{1}{2\pi i} \int_{\Gamma} \frac{f(z)dz}{z^{k+1}} - R_1 - R_2 \quad , \qquad (16)$$

Where $\Gamma$ is any origin centered circle with radius greater than $p_2$ where $R_1$ and $R_2$ are the residues of $f(z)/z^{k+1}$ at the poles $p_1$ and $P_2$. Thus

$$R_1 = 1/(p_2 - p_1)\, p_1^{k+1} \quad \text{and} \quad R_2 = -1/(p_2 - p_1)\, p_2^{k+1} .$$

Finally one may conclude that

$$s_k = \frac{1}{\sqrt{5}} \left[ \left(\frac{1+\sqrt{5}}{2}\right)^{k+1} - \left(\frac{1-\sqrt{5}}{2}\right)^{k+1} \right] . \qquad (17)$$

Equations (13) and (17) give a formula for the cumulative replicas:

$$S_k = \frac{1}{\sqrt{5}} \left[ \left(\frac{1+\sqrt{5}}{2}\right)^{k+3} - \left(\frac{1-\sqrt{5}}{2}\right)^{k+3} \right] - 1 \quad . \qquad (18)$$

At this point, if not before, the reader will probably try a few examples since these surprising formulas abound with irrational numbers and $S_k$ and $s_k$ are both integers.

For $n > 2$ similar expressions may be derived; however, they are not as compact as those above. For $n = 3$, $s_k = s_{k-1} + s_{k-2} + s_{k-3}$,

$$1/(1 - x - x^2 - x^3) = \sum_{k=0}^{\infty} s_k\, x^k$$

and the total number of replicas after k periods is $S_k = 1/2\,(3s_k + 2s_{k-1} + s_{k-2} - 1)$. For arbitrary n, $s_k = s_{k-1} + s_{k-2} + \ldots + s_{k-n}$ and alternatively each $s_k$ may be calculated by division, in that

$$\frac{1}{1 - \sum_{k=1}^{n} x^k} = \sum_{k=0}^{\infty} s_k\, x^k \quad . \tag{19}$$

We now address the more complicated system which exists in describing the number of replicas at each time interval when the restriction of a fixed number of generations m is imposed (Option a). We will now slightly change our notation by adding another subscript. $s_{m,k}$ denotes the number of replicas generated during the $k^{th}$ interval where m is the number of generations.

As an example let us consider Figure 11 where n = 2, m = 3. One observes that the diagram is the same as Option b until the limited number of generations begin to curtail replication, equality ceases after k = 3. One also observes that adding one more generation would add two replicas for each with a maximum of m ancestors. This would add a total of $2^m$ replicas. We find the sum after m generations by adding the terms, thus

$$S = \sum_{j=0}^{m} 2^j = 2^{m+1} - 1 \quad , \tag{20}$$

since we have a geometric series. One would like to know the number of replicas produced during each time frame. This would essentially require $2^j$ being partitioned correctly with each part added to the right time frame. The binomial theorem $(1 + a)^m = \sum_{i=0}^{m} \binom{m}{i} a^i$ with a = 1 gives a possibility

$2^m = \sum_{i=0}^{m} \binom{m}{i}$ and a careful counting argument establishes that $s_{m,m+i} = s_{m-1,m+i} + \binom{m}{i}$ $i = 0, 1, \ldots, m$. The general formula for any n is

$$
s_{m,k} = \begin{cases} \sum_{i=1}^{n} s_{m,k-i} & k = 0, 1, \ldots, m \\ \\ s_{m-1,k} + \sum \binom{m}{m_1 \ldots m_n} & k = m, m+1, \ldots, nm \end{cases} \tag{21}
$$

where the last summation is taken subject to $m = \sum_{i=1}^{n} m_i$ and

$k = \sum_{i=1}^{n} im_i$ and any $s_{m,k}$ with negative subscript is zero.

An easier formula to apply may be obtained by making use of the fact that each replica was produced during one of the previous time intervals and may have been from any of the previous generations. For example with n = 2, and the k-1 and k-2 time interval, there exist two two cases with respect to the $K^{th}$ - time interval. Each replica in the k-2 interval is either a m-1 generation replica or not. If not, then by definition, it has an offspring in the k interval; if so, then the next generation puts one there. The same argument goes for the k-1 interval. Since that is the only way one may be placed, we have the relation

$$
s_{m,k} = s_{m-1,\ k-1} + s_{m-1,\ k-2} \quad \text{(see Figure 16)} \tag{22}
$$

The same argument holds for any n. Thus

$$
s_{m,k} = \sum_{i=1}^{n} s_{m-1,\ k-i} \ . \tag{23}
$$

This approach allows any schedule to be completed recursively. The only difference between option a and b is that for Option b, m equals $\infty$, so that in effect $s_{m,k} = s_{m-1,k}$; that is, generations are not an issue and we drop the m in the notation.

## 7.0 SELECTED AREAS FOR FURTHER STUDY

### 7.1 SRS Field Complexity Versus Single Plant Complexity

It is important to know the difference in technology investment between self-replication and production. There must be a threshold where self-replication becomes economical compared with a single large production plant. This area requires intensive study.

### 7.2 Reliability Requirements

The reliability of components limits the complexity of the automata we can build, and self-replication requires automata of considerable complexity.

Any self-replication process is able to undergo inheritable mutations or random changes of one or more elements. If this happens the system will usually not completely replicate itself. A random mutation is most probably lethal or sterilizing but may be nonlethal and inheritable.

These mutations may be compounded such that either replication stops or nonfunctional systems are constructed. The potential rapid build-up of mutations must be investigated and the minimum required reliabilities established.

### 7.3 Economical Self-Replication

This will depend on a very high degree of commonality between the parts of the various systems. New design approaches must be developed that may stress commonality over functional efficiency. Section Section 3.2.

### 7.4 Totally Mobile UC

The option of a totally mobile UC should be investigated to reduce time of construction and waste. In this case, the MCC must be divided and separated so the operational MCC stays with the primary and the replication MCC moves with the UC.

## 8.0 A PROPOSED DEVELOPMENT AND DEMONSTRATION PROGRAM FOR SRS

### 8.1 Overall Program Objectives

The overall objective of an SRS Development and Demonstration Program is to develop an operational SRS to provide a variety of mass products from large areas of terrestrial and non-terrestrial raw materials autonomously and efficiently.

More specifically the objectives are:

a) To provide specific focal points for technology development.

b) To provide criteria for the development of required logic and mechanical systems of stepwise increasing complexity and their reliability and failure modes.

c) To investigate and solve for technology deficiencies.

d) To generate a model that will provide data and information for future mission planning (development schedules and cost).

e) To evolve toward an operational autonomous SRS.

f) To present to the technical and scientific community a new technology.

g) To provide new opportunities for an advanced space program.

### 8.2 Approach

The complexity of an SRS system requires a careful, stepwise approach toward development and demonstration. This approach is supported by the basic anatomy of an SRS system which can be readily designed in a highly modular way that allows a gradual expansion from basic technologies and demonstration objectives toward an ultimate "all-up" operational systems demonstration and capability. Most developments and demonstrations can be carried out on the ground at various locations. As a minimum demonstration goal the self-replication process should cover at least two generations of one replica each to verify proper information transfer.

The total SRS development and demonstration program will consist of four major phases, each of which will have numerous intermediate steps. The four phases are (Fig. 18):

a) Self-replication of the Universal Constructur (UC) from finished parts of subassemblies.

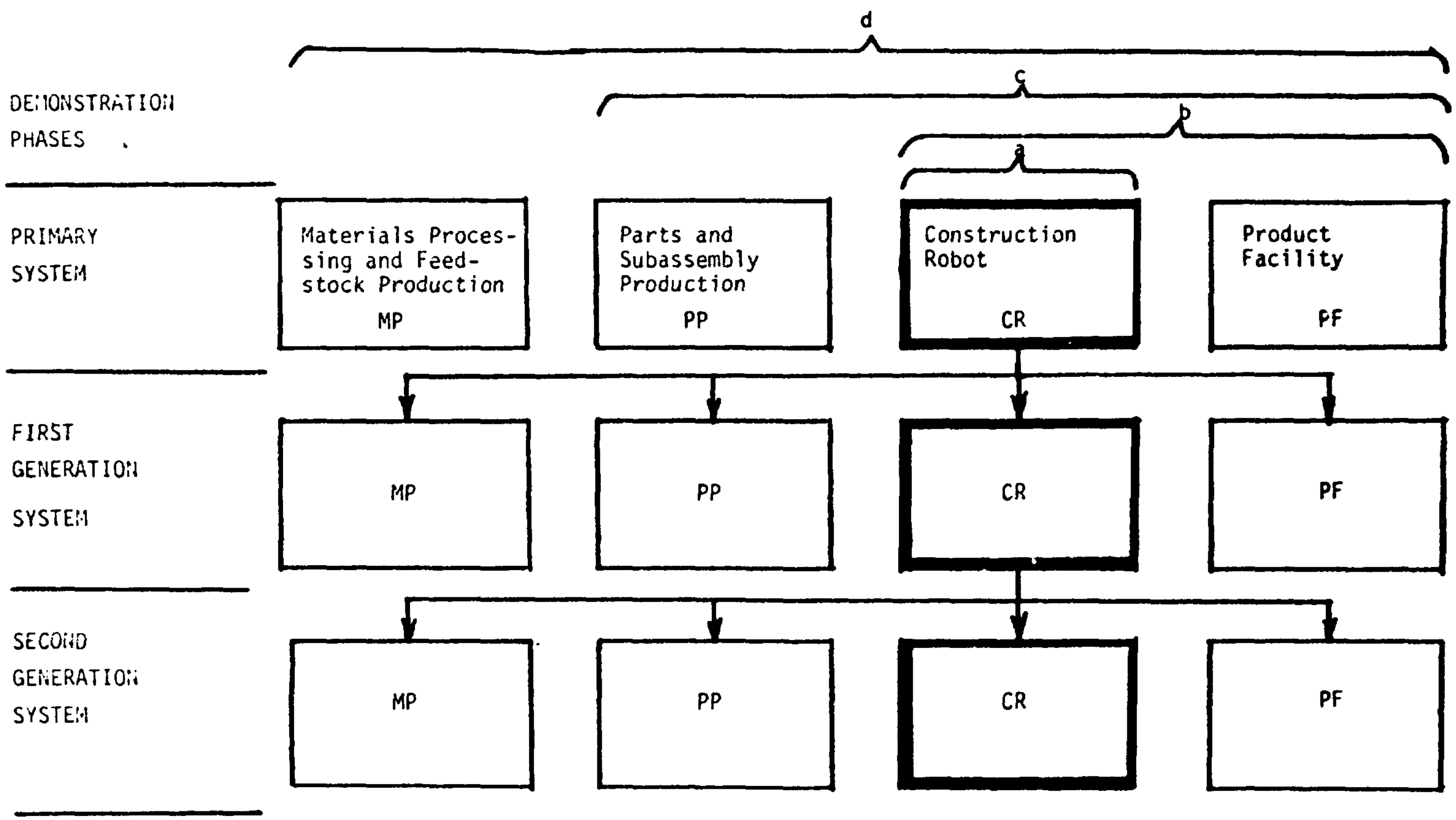



Figure 18. Schematic of demonstration phases.

b) Addition of a product facility (PF).

c) Addition of parts production from feedstock (PP).

d) Addition of feedstock production from raw material processing (MP).

The total development time is estimated to be 20 years with a major decision point in the sixth year. The first basic demonstration of a construction robot self-reproduction should be possible after 5 years from the start of the development (Fig. 19). The individual development steps are briefly described here.

8.2.1 Theory, Conceptualizations, Preliminary Concept Design.

This first step in the evolutionary process toward an operational SRS will include the theoretical background for the selected kinematic von Neumann option and develop engineering concept options for overall systems layout including instruction replication, hardware reproduction, systems operation and management and selected products. It will also include application options and a description of a selected reference application as the basis for a development program. The results of this step will include a preliminary concept design.

This step will be repeated during the early phase of the system analysis in order to survey new situations which may evolve from technology developments and the demonstrations of subsystems.

8.2.2 System Analyses

This effort will be continuous during the entire SRS development and will be the classical format which does not need elaboration here. This will be a rather sizable effort involving the generation of a totally new industrial production system and which will require a major organizational and managerial approach and effort.

8.2.3 Technology Development

This effort will have to respond continuously to the requirements originating from the systems analysis and includes computer, communication, materials, production and assembly, and autonomous systems management technology. It covers both hard- and software development. Results must be fed back into the systems analyses to provide trade-off data and systems and subsystems characteristics and performance parameters.

8.2.4 Technology Verification

As soon as technology data and requirements become available, verification efforts under simulated conditions on the ground or in space, as required, will proceed. Close coordination between development and verification must be maintained.

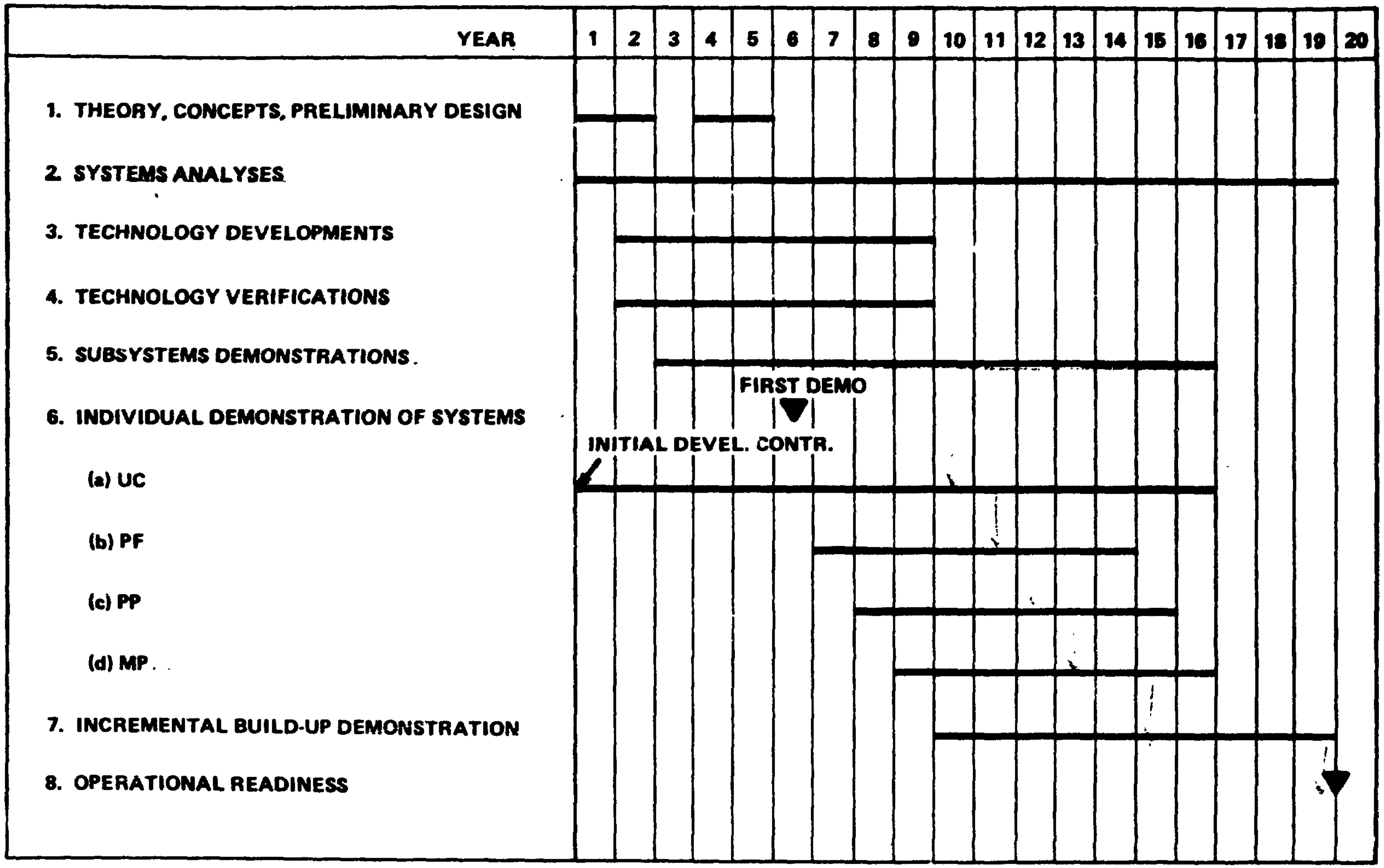



Figure 19. SRS development and demonstration program.

8.2.5 Subsystems Demonstrations

This key effort will be an important basis for a major decision point. Its objective is to demonstrate the performance characteristics of the partially integrated, previously verified operational conditions. The result of these efforts will verify all theoretical and technological efforts to date and serve as a qualification for subsequent individual systems demonstrations.

8.2.6 Individual Demonstrations of Systems (Ground)

If the decision is made to proceed from the subsystems demonstrations, the systems must be demonstrated in their entirety. This involves the following individual integrated systems: Construction Robot (CR), Product Facility (PF), Parts Production (PP), and Materials Processing and Feedstock Production (MP).

Each demonstration can be performed at different locations as is practical and will run with predetermined, simulated interfaces. These 10-year demonstrations constitute the major phase of individual systems performance, efficiency, requirements, antonomy and reliability determination in preparation for a development toward an all-up demonstration.

Each system will be demonstrated in each step of its evolution, e.g. the CR will demonstrate four successive capability designs: reproduction of itself, itself plus a PF, itself, a PF plus a PP, and finally an all-up capability. The PP demonstration will be performed in a similar sequence.

8.2.7 Systems Demonstration With Incremental Build-Up to an All-Up System

After the individual systems demonstrations have run successfully this phase will perform an incremental uild-up of the final versions of each system ending up in all-up demonstration in a simulated environment and under the closed possible operational conditions. This demonstration will be performed over several generations with several replicas each.

After final all-up runs the system can be declared ready for lunar applications.

The emplacement time of the first operational primary SRS will depend on transportation availability and scheduling which is not covered here.

The initial operational emplacement will follow a predetermined start-up plan which will increase autonomy at a rate which is determined by the build-up of confidence in the system. Simultaneously control and maintenance of personnel will be decreased.

## 8.3 Fundamental Development and Demonstration Program Requirements (Table 3)

To establish a first order set of development and demonstration requirements, we shall define the requirements of each of the basic four elements of an SRS as we progress through the four phases of the development and demonstration program. It should be noted that the last phase should be equivalent to an operational system, though probably different in scale.

### 8.3.1 Construction Robot (CR)

In phase a: The CR's sole task is to construct a replica of itself from furnished parts and subassemblies which are readily delivered to the CR. The parts and subassemblies include any jiggs and fixtures required for construction. Phase a could proceed from a rather simple CR to more complex ones in discrete steps. The last step should approach the complexity required by the phase b demands.

In phase b: A Product Facility (PF) will be added to the CR. Therefore, in addition to constructing a replica CR, the required number of Production Robots (PR's) must be constructed by the CR. The PR's are reprogrammable robots commensurate with the desired product production.

In phase c: We add Parts and Subassembly Production (PP) to the CR. This requires from the CR the construction of a number of Parts and Subassembly Production Robots (PPR's) in addition to construction a CR and PR's. The PPR's have to produce parts and subassemblies for PPR's, a CR and PR's.

In phase d: We add as final element a Materials Processing and Feedstock Production Facility (MP) to the system. The MP has Materials Processing Robots (MPR's) and Feedstock Production Robots (FPR's). The required parts and subassemblies for these must be added to the capabilities of the PPR's and the required construction of these must be added to the CR capabilities. Table 3 shows this evolution in a systematic and schematic way.

### 8.3.2 Production Facility (PF)

This facility will be added in phase b and may have far reaching commonality with the PP to be added later in phase c. It operates with PR's assembled by the CR.

### 8.3.3 Parts and Subassembly Production (PP)

In phase c, the PP will have to produce its own parts in addition to the parts required to assemble a CR and the PR's. In phase d the PP will have to produce the parts for the MPR's and FPR's in addition to its own parts and those of the CR and the PR's.

TABLE 3. FUNDAMENTAL REQUIREMENTS OF SRS ELEMENTS

| SRS BASIC ELEMENTS / DEMO. PHASE | MATERIALS PROCESSING AND FEEDSTOCK PRODUCTION (MP) | PARTS AND SUBASSEMBLY PRODUCTION (PP) | CONSTRUCTION ROBOT (CR) | PRODUCT FACILITY (PF) |
|---|---|---|---|---|
| A | | | EQUIPMENT: CR<br>TASK: CONSTRUCTION OF CR | |
| B | | | TASK: CONSTRUCTION OF CR, PR's | EQUIPMENT: PRODUCTION ROBOTS (PR's)<br>TASK: PRODUCT PRODUCTION |
| C | | EQUIPMENT: PARTS PRODUCTION ROBOTS (PPR's)<br>TASK: PARTS PRODUCT, FOR PPR's, CR, PR's. | TASK: CONSTRUCTION OF CR, PR's, PPR's | ↓ |
| D | EQUIPMENT : MATERIAL PROCESSING AND FEEDSTOCK PRODUCTION ROBOTS (MPR's, FPR's). TASK: MATERIAL PROCESSING AND FEEDSTOCK PRODUCTION FOR MPR's, FPR's, CR, PR's, AND PPR's. | TASKS: PARTS PRODUCTION FOR PPR's, CR, PR's, MPR's, FPR's. | TASK. CONSTRUCTION OF CR, PR's, PPR's, MPR's, FPR's. | ↓ |

### 8.4 Technological Considerations

a) Definition of a basic set of multipurpose tools and machinery with a maximum in flexibility. This will automatically lead toward tools and machinery that can self-replicate (see Section 3.0 for details).

b) Definition of basic multipurpose mechanical, electrical and electronic elements and building blocks. This will lead toward a maximum of commonality of building and machine elements.

c) Tradeoffs should be made between numerous single-purpose machines that are relatively simple and easy to replicate and limited numbers of multi-purpose machines that are complex and more difficult to replicate.

### 8.5 Demonstration Phase a

#### 8.5.1 Objectives

a) To demonstrate the replication of a robot and necessary peripheral equipment including the logic system over two generations producing one replica in each generation.

b) To generate information on the reliability and failure modes of the replication process and the replicas both in the logic and the mechanical systems.

c) To achieve operational confidence in the system and provide an approach for the addition of a production facility.

#### 8.5.2 Approach

A possible development sequence toward the objectives of phase a is as follows (Fig. 20):

1. Define assembly sequence of CR -- here we will devise successive steps of complexity by defining a series of assembly tasks from subassemblies down to complete assembly from individual parts.

2. Define assembly tools, fixtures, equipment, etc. – All auxiliary assembly aids must be defined because they will have to be included in the replication process, an early option may be their inclusion in the parts delivery.

3. Substitute manual assembly phases by special tools, fixtures, equipment, etc. – It can be readily assumed that certain manual labor is involved in the conventional CR assembly. Substitute equipment has to be developed and included in the self-replication process, an early option would be their inclusion in the parts delivery.

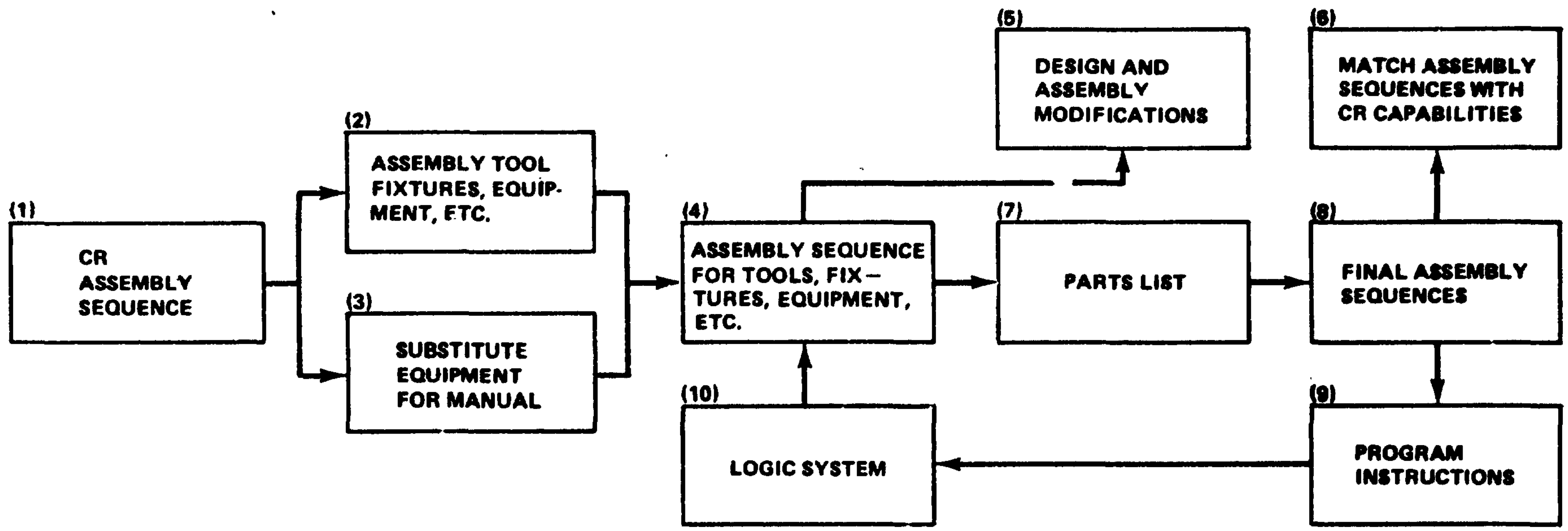



Figure 20. SRS demonstration, phase a development task flow.

4. Define assembly sequences of tools, fixtures, and equipment (including logic system) – The assembly sequences of both primary and substitute tools, fixtures, equipment, etc. have to be established in addition to the CR assembly sequence (task 1).

5. Define design and assembly modifications – Any design or assembly modifications must be considered here which result from automated assembly requirements. The results must be fed back into tasks (1) through (4).

6. Match assembly sequences with CR capabilities – These sequences must be matched with the CR capabilities. Any changes must be fed back into task (5).

7. Parts list – A complete parts list can be drawn up now.

8. Final Assembly Sequences – The complete self-reproduction sequence can now be described.

9. Program Instructions – A computer program can now be written.

10. Logic System – A logic system must be designed to receive the program instruction including the capability of copying the program instruction at the end of the self-reproduction phase.

8.6 Demonstration Phase (b)

8.6.1 Objectives:

(a) To demonstrate the replication of a PF in addition to the replication of a CR (phase (a)) including controls and logic systems over two generations producing one replica in each generation.

(b) To generate information on the adaptability of the CR to additional tasks and on the reliability and failure modes of the replication process and the replicas both in the logic and the mechanical system.

(c) To introduce the division of activity of the stationary and mobile part of the CR required to construct the PF.

(d) To achieve operational confidence in the system and to provide an approach for the addition of a PP.

8.6.2 Approach

Depending on the desired product a set of PR's are defined that are capable of assembling this product at the desired production rate. These PR's should have maximum similarity to the CR to minimize the additional tasks of the CR to assemble PR's.

(a) Define assembly sequence of PR's. Successive steps of complexity will be devised by defining a series of assembly tasks from subassemblies to individual parts.

(b) Define assembly tools, fixtures, equipment, etc. All auxiliary assembly aids must be defined and will form a part of the parts delivery. Define also any assembly sequences of this equipment.

(c) Develop CR capabilities based on the requirements above.

(d) A parts list can be drawn up now.

(e) Describe the complete CR + PF self-reproduction sequence.

(f) Develop a computer program and the logic systems for the CR-MCC and the production program.

8.7 Demonstration Phase (c)

8.7.1 Objectives:

(a) To demonstrate the minimum closure of a universal parts production system from feedstock.

(b) To demonstrate an extensive, universal parts production capability from feedstock under fully automated and controlled conditions.

(c) To demonstrate parts recognition, programmed parts production rates, automated sorting of parts by subsystems and required subsystems assembly, and by SRS systems.

(d) To demonstrate reliability and failure modes of PPR's

(e) To demonstrate the extended CR capability of assemblying CR's, PR's, and PPR's and to show the site location and assembly sequencing capabilities of the MCC in conjunction with the MUC.

8.7.2 Approach

Here we have for the first time machining operations performed by PPR's. We determine the number of types of machine operations that must be performed to make the parts for the PR's and CR's. Then we select the PPR's that can perform these machining operations. Now we check the necessary machine operations to produce the parts of the PPR's. These may either be identical to the operations required for the PR's and CR's or may need additional operations not yet covered. This then requires the addition of PPR's to cover these additional machining operations. In order to "close" the system as soon as possible the PPR's shall be designed for maximum commonality of parts. In this phase the CR's will now have the additional task of assembling PPR's in addition to PR's and CR replication. Therefore, the CR of this phase could be a new design with extended capabilities or an extension of the CR in phase (b) if feasible.

## 8.8 Demonstration Phase (d)

### 8.8.1 Objectives:

(a) To demonstrate an "all-up" SRS.

(b) To demonstrate the material processing from new material to feedstock for lunar materials or equivalent. As an option terrestrial materials for potential terrestrial applications can be processed.

(c) To demonstrate "closed-loop" materials processing with complete processing agents recovery.

(d) To demonstrate automated materials analyses and recognition and automated process adjustments.

(e) To demonstrate the SRS traffic and transport systems (MUC, PRS).

(f) To demonstrate the growth of the EPA and ES through incremental additions.

### 8.8.2 Approach

This will be the basis for an "all-up" system. We determine the material requirements of all parts of the system (CR, PR, PPR, FPR and MPR) and compare those with available raw materials. With proper planning including materials substitutions a match between available materials and requirements will exist. Parts for which no material exist must be furnished. The necessary materials processes and feedstock production phases are now analyzed as to their robot requirements (MPR's and FPR's) and the robots are defined. Again maximum commonality of parts among them and the rest of the robots is of utmost importance to achieve a reasonable and early closure rate at the PPR's. The final CR now requires an assembly capability of the total system and should be optimized for this task. This done, another complete parts and machine operations analysis will determine the final stable of PPR's.

## 8.9 Conclusion

1. The initial CR could be rather limited in its capabilities, just sufficient for self-replication from parts and subassemblies.

2. It is important that each phase has intermediate steps that lead from basic initial requirements of the first step to the initial requirements of the next phase to provide for a gradual and manageable increase in complexity.

3. Each element of Table 3 requires a detailed analysis based on a set of assumptions to be postulated at the outset.

4. The definition of the individual elements of the SRS is a highly iterative process, e.g. the configuration of an MPR depends on the material requirements of parts to be produced by the PPR's; however, these parts partially depend on the type of materials to be processed which affects the configuration of the MPR, etc.

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# APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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