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Study on Utilization of Lunar Energy

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Study on Utilization of Lunar Energy

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Contents

Part 1

Glass Ocean Subcommittee

1. Introduction

For activities on the moon, it is important for us to secure energy in the nighttime. The moon has a night that lasts for a period of approximately 14 days and has a surface temperature that drops to approximately -170°C on the equator. For human beings and equipment to carry out a mission on the moon for a long period, it is a significant challenge in the moon exploitation/utilization concept to secure a steady energy source, including the protection of both human beings and equipment against such a severe cold environment on the moon.

This paper is intended to deal with the "Glass Ocean System" which was studied for fiscal 1994 as a new concept system capable of supplying a stable energy produced on the moon.

2. Outline of Glass Ocean Concept

2.1 Outline of Glass Ocean Concept

It is known that one of the features on the regolith of the moon is a very low thermal conductivity and a constant temperature several tens of centimeters under the surface day and night (-20°C around the equator). From this, it may be gathered that the regolith on the moon functions as a kind of excellently heat-insulating thermos bottle.

In this thermos bottle, a heat storage agent is to be generated using materials available on the moon. In the daytime which lasts for 14 days, a solar heat collector is to be used to warm the agent, which is in turn to be used as an energy pit (hot-water bottle). The heat so stored may be used either as heat itself or electric power by thermal electric conversion. This hot-water bottle is to be popularly named as the "glass ocean."

The wording "glass ocean" originates from an expression of the thermal storage material. One of the thermal storage materials now considered promisingly available is the regolith which might well be molten in a solar heat collector (at a melting point of approximately 1,400 thru 1,700K), classified and made massive (like blocks). For other thermal storage material candidates, furthermore, there are ideas such as using blocks made by chemical reactions (combustion), and a mixture of powdered regolith with a gas such as helium or nitrogen.

In the daytime on the moon, this glass ocean is to be heated up to approximately 800 thru 1,000°C by the use of a solar heat collector while the temperature difference between the glass ocean and the moon surface (about -170°C on the equator) is utilized in the nighttime to generate electricity. In the daytime, the glass ocean is heated with the solar heat collector while simultaneously generating electricity, using the temperature difference between the solar heat collector and the moon surface.

Fig. 2.1-1 shows an outline of the glass ocean system concept.

From the outside, the glass ocean looks like a glass mare embedded in the regolith on the moon. A solar heat collector unit, a power generator unit and a radiator unit are located on the surface of the moon. It may be considered possible, moreover, that the glass ocean constructed on the moon surface may be coated with the regolith later. The performance of the glass ocean largely depends upon the heat transfer efficiency. It is necessary, therefore, that a heat pipe, a metal plate, etc. should be inserted so as to come into full contact with the glass ocean.

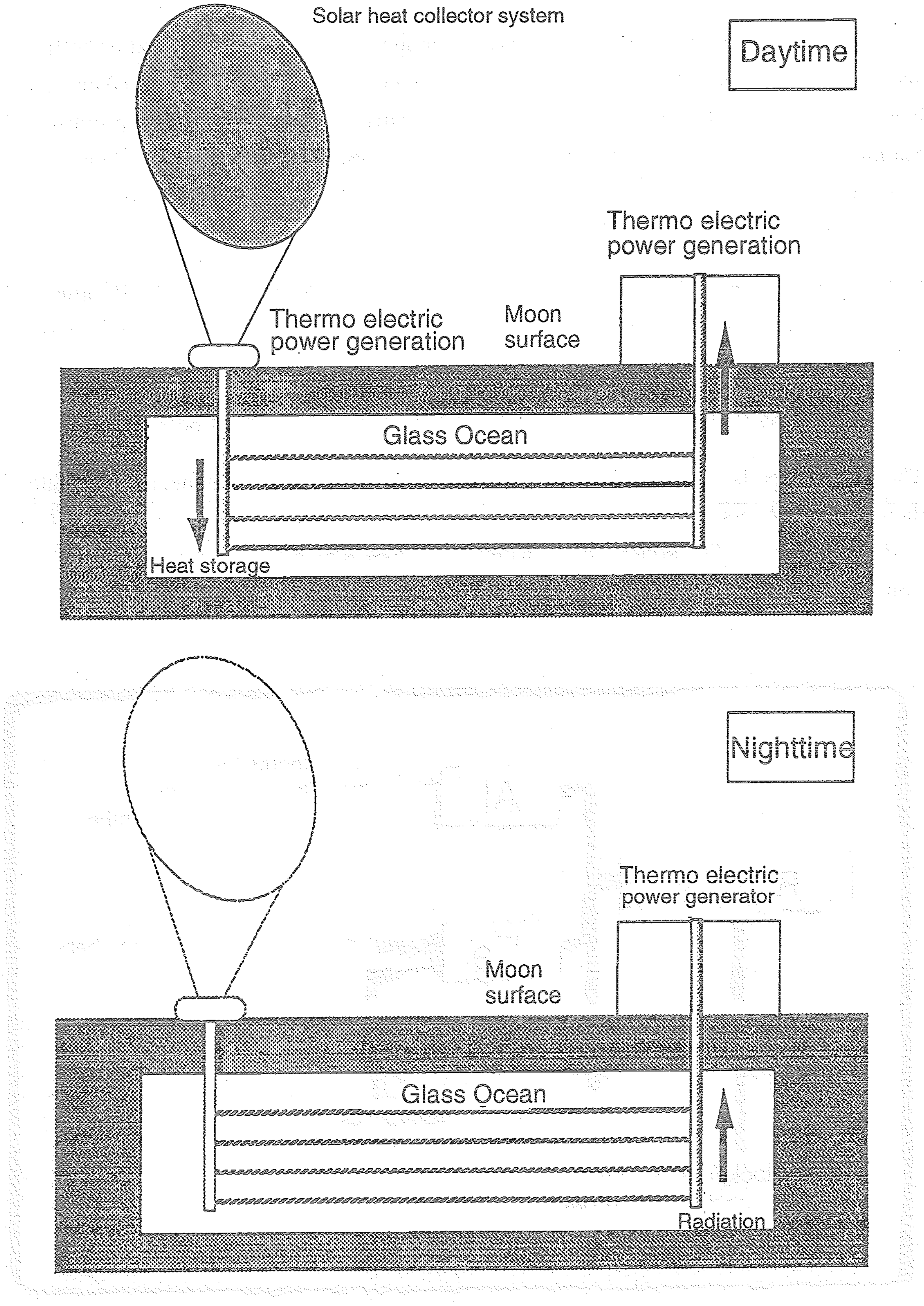


Fig. 2.1-1 Schematic, Glass Ocean Concept

2.2 Securing Self-Proliferativity

As one of the significant problems involved in mapping out a moon exploitation/utilization scenario, it should be pointed out that an immense volume of things needs to be taken from the earth to the moon. In a variety of moon base construction scenarios so far proposed, the haulage cost has occupied a very large percentage of the total investments. To realize the economic exploitation/utilization of the moon, it is necessary to minimize the cost incurred by the haulage.

With such problems taken into consideration, the Glass Ocean system should aim at the maximum use of resources available on the moon and at self-proliferativity, based on energy produced on the moon.

Fig. 2.2-1 shows the effective utilization of lunar resources in the glass ocean.

The main minerals composing the regolith are pyroxene, feldspar, olivine, and ilmenite. In these forms, a diversity of elements exists on the moon. As averaged on the overall overburden of the moon, more than 80 percent by weight is occupied by four elements, oxygen, silicon, iron and aluminum (of which a little more than 40% is occupied by oxygen).

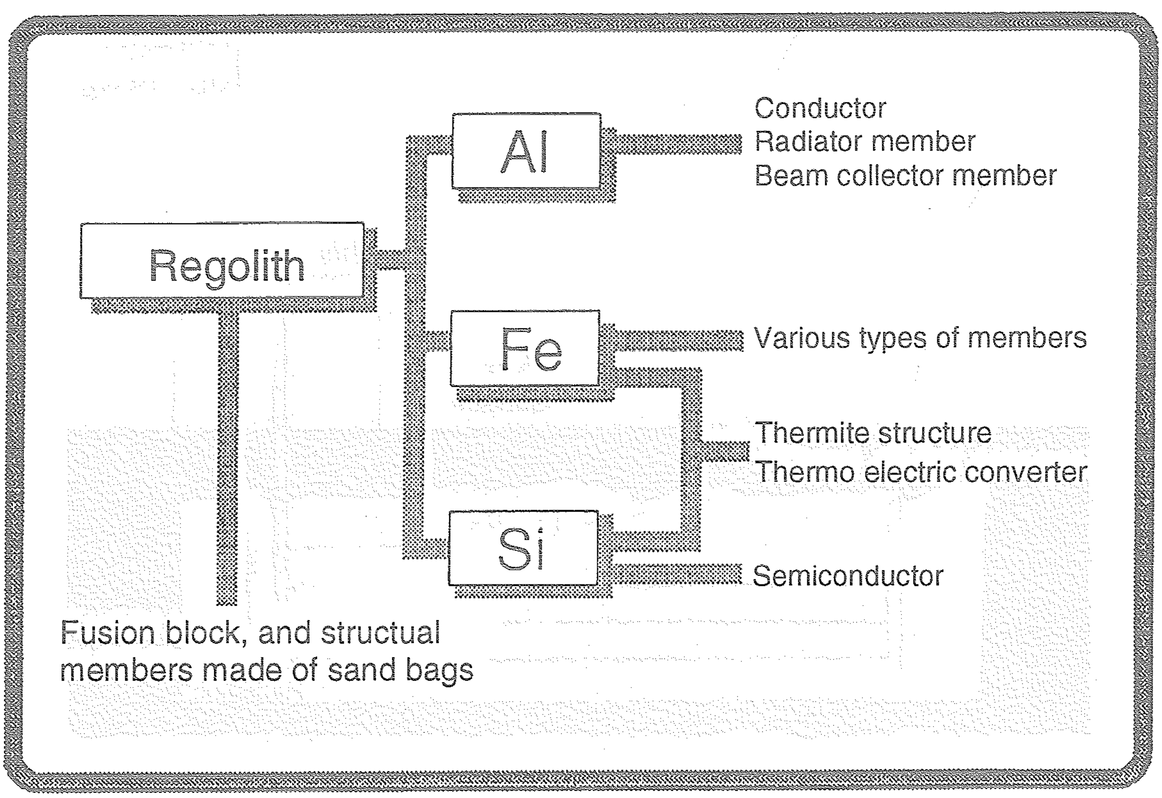


Fig. 2.2-1 Effective Use of Lunar Resources in Glass Ocean

To bring about substantial use of the moon in the face of the challenges already referred to, it would be best to make the most of those elements abundant on the moon surface. To secure the self-proliferativity of the glass ocean system, the lunar resources may be considered utilizable as follows:

- Regolith
    - Heat the regolith in a solar beam collector furnace to make fusion blocks.
    - Pack such fusion blocks in sand bags, which are to be in turn used as structural members.
- Iron
    - Make various types of members and mechanical parts.
- Aluminum
    - Make conductors of aluminum as a copper substitute.
    - Make radiator members.
    - Make beam collectors especially on the surface.
- Iron Oxide (ilmenite) + Silicon
    - Materials required for a silicone thermite reaction to form members and blocks [a combustion synthesization of (iron oxide = ilmenite) + silicon → iron (+ titanium) + silicic acid]
- Iron + Silicon
    - Producing a thermo electric converter of iron silicate
- Silicon
    - Producing semiconductors (power amplifiers, etc.)

Once the glass ocean has allowed a certain level of electric power to be produced on the surface of the moon, it becomes possible to extend the system on a self-proliferative basis by producing the above-mentioned substances using lunar energy.

2.3 Outline of Thermal Storage

The regolith has a thermal conductivity of approximately 0.01W/m・K[1]. It may be considered as an excellent heat insulator as compared with glass wool, blankets, wool, asbestos and cork, all of which have a heat transfer range of 0.04 thru 0.06W/m・K[2]. This excellent heat insulation originates from the powdered condition of the regolith.

With the glass ocean assumed to have an initial temperature of 1,000°C, a drop in temperature due to radiating heat has been calculated while reckoning the regolith surface's radiation of 0.92[3]. For this calculation, the SINDA (Systems Improved Numerical Differentiating Analyzer) has been used. The glass ocean has a temperature drop of approximately 23°C in the moon nighttime (14 days) at a regolith thickness of 1.0 meter on the glass ocean and of about 43°C at a regolith thickness of 0.3 meters. Thus, the regolith has been proved to have a sufficient capacity as a heat insulator. (Figs. 2.3-1 and 2.3-2)

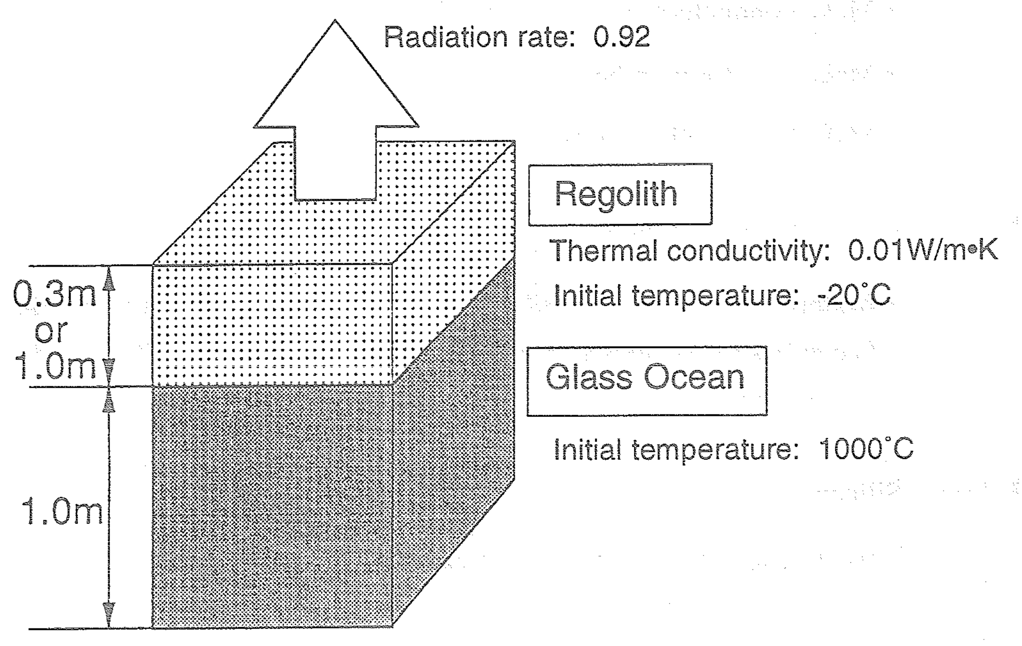


Fig. 2.3-1 Analytical Model

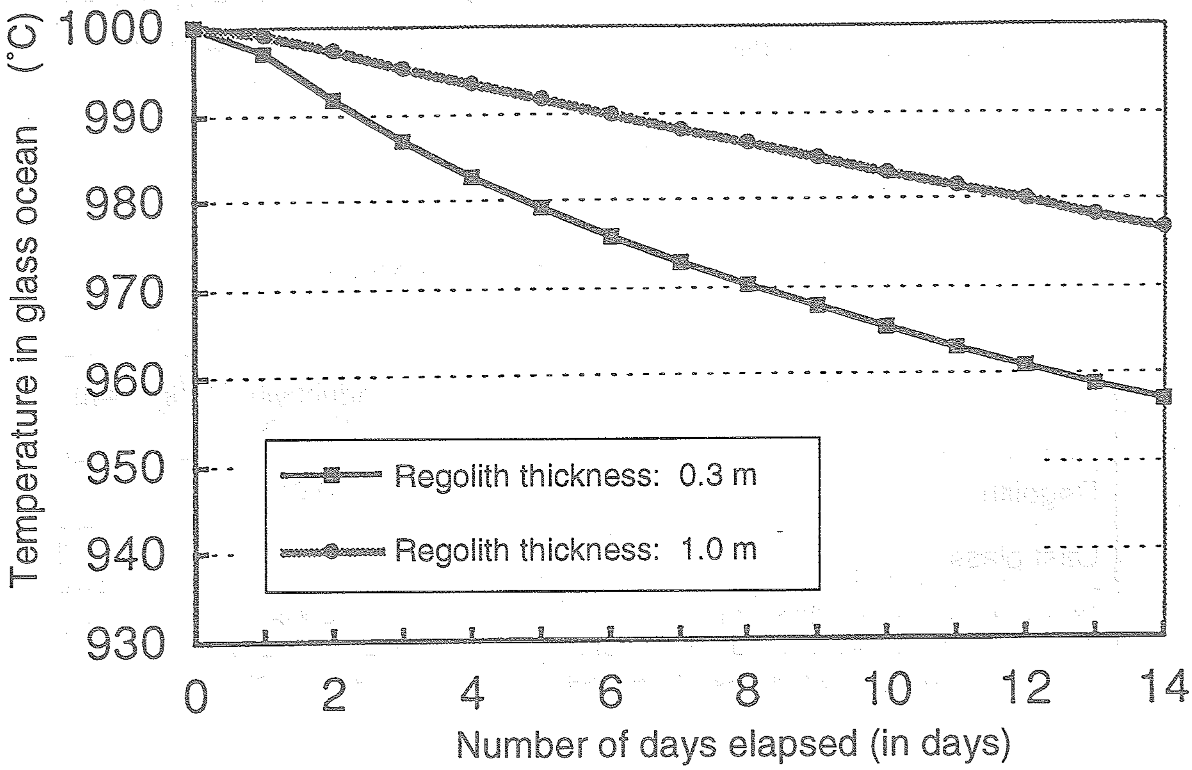


Fig. 2.3-2 A Drop of Temperature in the Glass Ocean

A description is given below of the thermal storage. Quartz glass has a thermal conductivity of 2W/m•K[(2)]. It is predicted that the glass ocean, a solid of the lunar regolith once molten, has a thermal conductivity near to that of quartz glass. The difference in thermal conductivity from the regolith is used to make a flow of thermal energy, which is in turn converted to an electric energy by the use of a thermo electric converter or the like.

Table 2.3-1 shows the thermal conductivity of various materials which are likely to make up the glass ocean system. Any of these materials is considered to have a thermal conductivity of about one hundred times that of the regolith. From this, it can be gathered that the heat may be stored by a wide diversity of methods.

Table 2.3-1 Thermal Conductivity by Material

Material	Thermal conductivity (estimated) W/m•K
Regolith	0.01
Cast glass	2 ~ 2.5
Thermite material (SiO_2+Fe)	> 1.6
Regolith in which helium gas is mixed	0.84 ~1.76[4]

References (2.3)

(1) NASA SP-330, Apollo 17 Preliminary Science Report, 1973

(2) Chronological Table of Science edited by National Astronomical Observatory, Maruzen

(3) JPL D-8160, Thermal Environment, 1991

(4) B. Tillotson, AIAA 91-3420, Regolith Thermal Energy Storage of Lunar Nighttime Power, 1991

2.4 Size of Glass Ocean

On the assumption that heat can be ideally stored and radiated at 0°C thru 1,000°C day and night, let's calculate the size of the glass ocean required to generate 100kW (order considered to be required for a lunar base in the initial stages) of electric power in the moon nighttime. It is supposed that the glass ocean is to be made of cast glass.

$$We = \eta \cdot Wm \cdot (Cph \cdot Th - Cpl \cdot T1)$$

where

We	:	Total electric power required for 14 days [1.21×10^{11} (J)]
η	:	Power generator system efficiency [5%]
Cph	:	Specific heat at 1,000°C [1.11 (J/g · K)]
Cpl	:	Specific heat at 0°C [0.70 (J/g · K)]
Th	:	Temperature, glass ocean (when hot) [1273 (K)]
T1	:	Temperature, glass ocean (when cold) [273 (K)]
Wm	:	Weight, glass ocean

Therefore, we can get Wm = approximately 1,980 tons. If the glass ocean has a density of 2.5 (g/cm^3), it will have a volume of approximately 792 (m^3). And the glass ocean is a cube whose sides are approximately 9.25 meters each (Fig. 2.4-1). As far as the specific heat of the glass ocean is concerned, data has been obtained from the quartz glass at 0°C and 500°C. The specific heat of a solid tends to increase as the temperature rises. In reality, therefore, the specific heat will be far higher at 1,000°C. And it is expected that the model specified herein will have a larger thermal storage capacity.

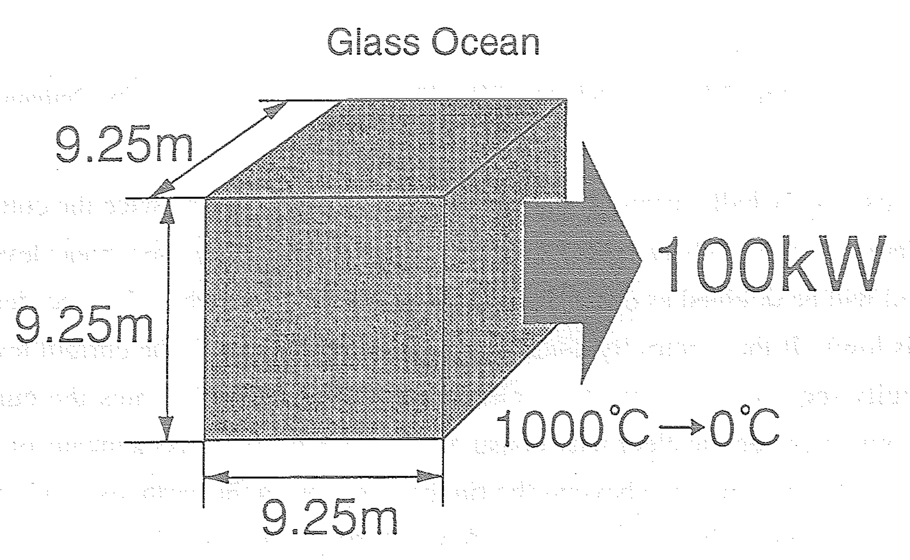


Fig. 2.4-1 Calculating the Size of the Glass Ocean

2.5 Transferring Energy to the Earth

An exhaustion of resources on the earth is a social problem at a worldwide level, which will be far more serious in the 21st century than ever. Great difficulties are expected to be encountered with energy resources, among others, coupled with an increase in the world population.

Fig. 2.5-1 shows a prediction of the increases in world population[1] and in demand for electric power.

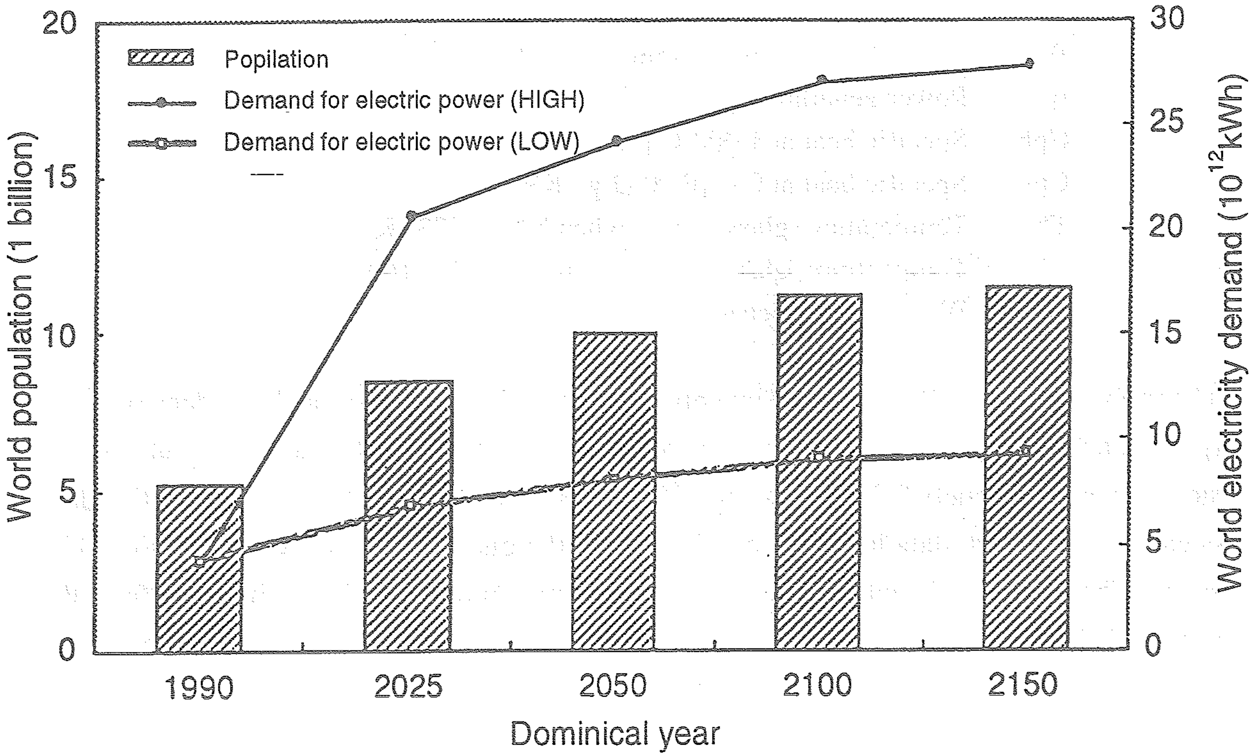


Fig. 2.5-1 Projections of World Population and Electricity Demand

In approximately half a century, the world population will reach twice the current level. If the electricity consumption per capita[2] is assumed to remain at the present mean level, the electricity demand will be doubled as compared with the present level (when the electricity consumption level is low). If the electricity demand per capita should reach the current level in Japan, the electricity requirement fifty years ahead will amount to five times the current electricity consumption (when the electricity consumption level is high). As a means of supporting such an energy demand increase beyond the finite resources on the earth, extra-global resources are available. And the glass ocean is considered usable as such an element.

The most significant feature of the glass ocean is that it is extensible on a self-proliferative basis. Making the most of this feature might well allow us to obtain a far larger return of energy than the initial investments (energy) made from the earth. The glass ocean system, moreover, has a smaller number of operating portions, being considered to have a far longer service life than that in a power generating system on the earth. It is, therefore, advantageous from an extension point of view, too.

Using the energy generated in the glass ocean system and the lunar resources already referred to will permit a new glass ocean system to be constructed without resorting to the resources from the earth as far as is practicable. And the electric power generated in the glass ocean system so extended is to be transmitted to the earth. Similarly to SPS, a microwave power transmission system will be available to transmit the electricity from the moon to the earth.

From this point of view, studies are being now underway into the feasibility of a power-generator plus power-transmission system, through which the 5GW power is transmitted from the moon to the earth, including an integration of related system components, and the possibility of constructing a system from lunar resources.

Fig. 2.5-2 shows an outline of the transmission system.

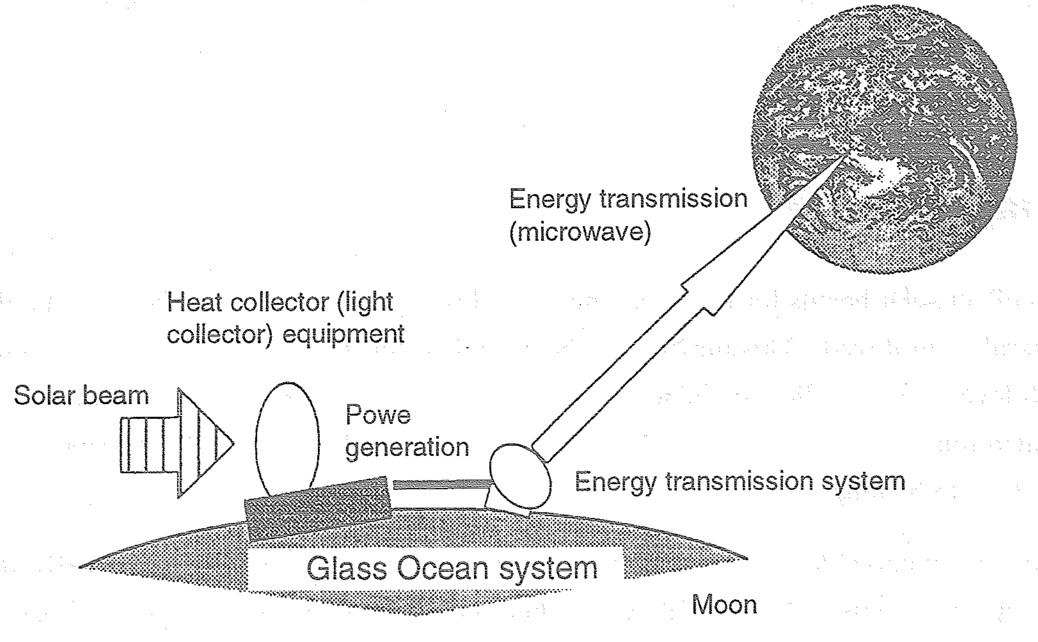


Fig. 2.5-2 An Image of the Moon-Earth Energy Transmission System

References (2.5)

(1) World Resources, 1992-93

(2) Comprehensive Energy Statistics, Planning and Survey Section, Director General's Secretariat, Agency of Natural Resources and Energy

3. Studying a 100kW-Class Power Generating System

3.1 System Trade-off and Feasibility Study

3.1.1 Comparing and Studying System Configurations

A glass ocean system is broadly composed of the following three portions:

- Heat collector unit

  Collecting solar beams and transferring their heat to a thermal storage unit,

- Thermal storage unit

  Storing the heat collected in the heat collector unit so that it can be used to generate the electricity in the nighttime, and

- Power generator unit

  Generating electricity in the nighttime, using the heat stored in the thermal storage unit in the daytime.

What is commonly contained in the units referred to above, moreover, is the heat transfer unit to store the heat on an inter-unit basis. In addition, a radiator unit is also included to generate the temperature difference required for the power generator unit to generate electricity.

(1) Heat Collector Unit

To collect solar beams for the obtainment of a high temperature, a parabolic heat collector is generally employed. This method has been studied for its practical use and found to have a high level of heat collection efficiency. Nevertheless, the heat collecting center needs to be located remotely from the parabola so that the heat transfer route to the thermal storage unit will tend to be long.

Another conceivable method is that in which the heat collector unit is conically shaped to collect solar beams at the top of the cone. In this case, the cone top is the heat collecting center so that the heat transfer route to the heat storage unit is relatively short. It is also structurally simple. Nevertheless, a certain incident angle might hinder beams from reaching the heat collecting center or might require two or more reflections for the solar beams to reach the center. As a result, this heat collector unit is less efficient in collecting heat than the parabolic type.

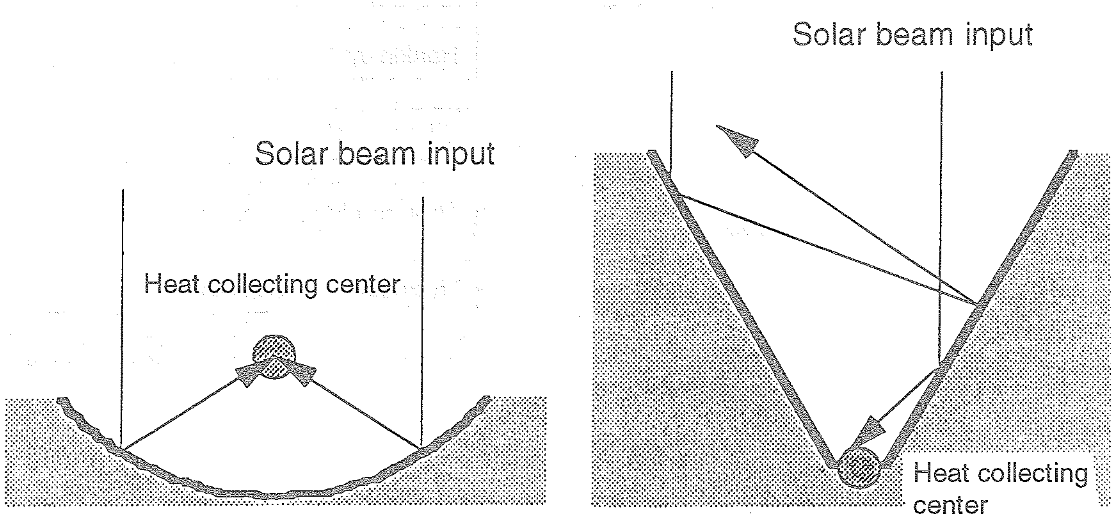


Fig. 3.1-1 Shapes, Heat Collector Unit

Moving the heat collector unit so as to directly face the sun would permit the heat collecting efficiency to increase. If this system should have a size enlarged to transmit the electricity to the earth, however, it would be realistically difficult to change the direction of the parabola, because the heat collector unit will be sized to a level of several ten meters thru several hundred meters.

From the above, it may be gathered that a stationary type parabolic heat insulator unit is appropriate for the glass ocean power generator system.

(2) Power Generator Unit

The heat collected must be converted to an electric energy by a certain means. The systems to convert heat to other energies may be classified as shown in Fig. 3.1-2[1].

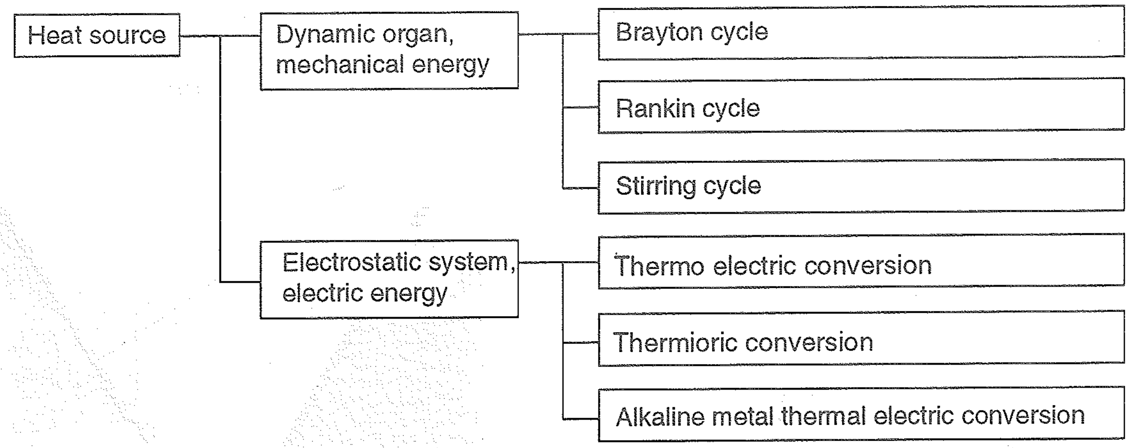


Fig. 3.1-2 Classification of Energy Conversion Systems

The system employing a dynamic organ is very highly efficient. Nevertheless, it requires advanced mechanical components, whose production on the moon is considered impossible anyway.

The technology which could be considered appropriate for employment in the glass ocean system would be such a system as to be relatively simply constructed and free from rotary parts while requiring little labor for maintenance and converting thermal energy directly to electricity. Thermo electric power generation may be considered the most promising at present from the viewpoint that the materials required to generate electricity on the moon are procurable with relative ease.

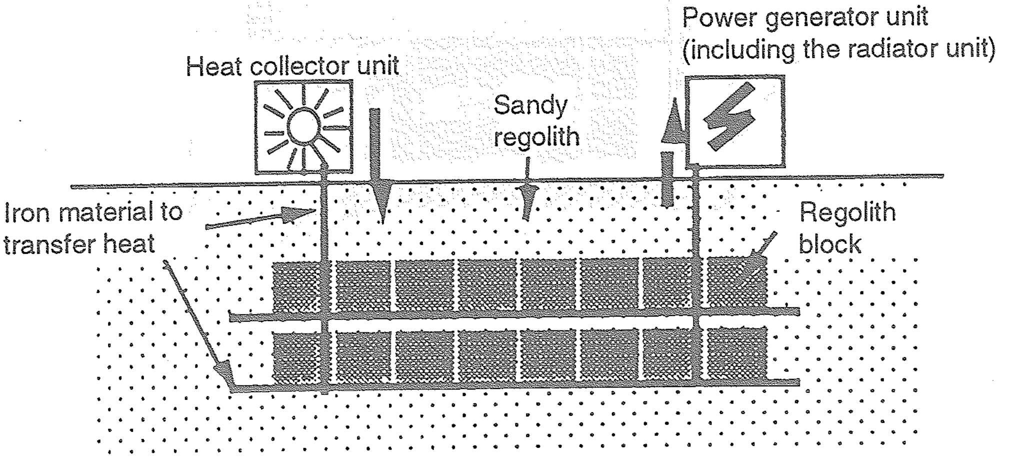
(3) Thermal Storage Unit

As far as the thermal storage unit is concerned, a few system configurations may be envisaged. Figs. 3.1-3, -4 and -5, respectively, show three different types of thermal storage systems.

In each system, the thermal storage unit is surrounded with sandy regolith, thereby forming a configuration to prevent the thermal storage unit from radiating by use of the regolith's excellent heat insulating property.

Those regolith blocks which are to be used as a heat storage element in Systems 1 and 3 are the regolith which has been molten (at a melting point of about 1,400 thru 1,700K) and solidified into blocks. And they may be considered to have a thermal capacity at a level identical with that of glass.

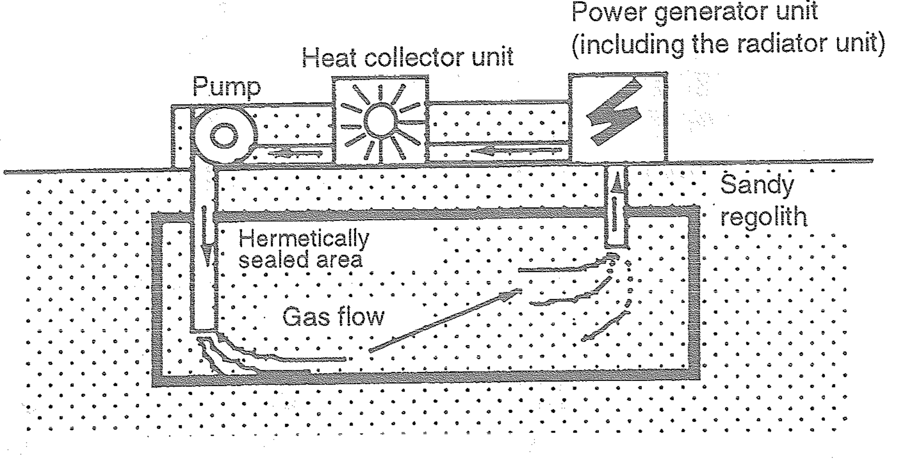
Those metal elements contained in the regolith, which occupy a large percentage, are silicon, iron and aluminum. As shown in Table 3.1-1 indicating their respective thermal conductivities, aluminum is the most highly thermally conductive[2].



Heat Storage Element : Regolith blocks which are the regolith molten and solidified.

Heat Transfer Medium : Flat plate-like or rod-like iron material made of iron which has been extracted out of the regolith.

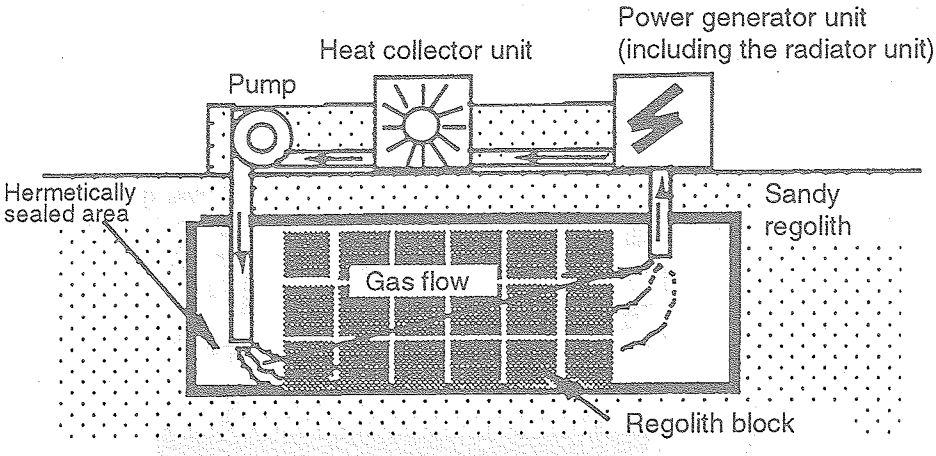
Fig. 3.1-3 Schematic, System 1



Heat Storage Element : Sandy regolith in its naturally existing state on the moon

Heat Transfer Medium : Nitrogen or helium gas

Fig. 3.1-4 Schematic, System 2



Heat Storage Element : Regolith blocks which are the regolith molten and solidified

Heat Transfer Medium : Nitrogen or helium gas

Fig. 3.1-5 Schematic, System 3

Table 3.1-1 Thermal Conductivity[2], Al, Fe and Si

	Thermal conductivity W/(m • K)		
Temperature K	Aluminum Al	Iron Fe	Silicon Si
150	248	104	409
250	235	86.5	191
300	237	80.3	148
600	232	54.7	61.9
800	220	43.3	42.2
1000	------	32.6	31.2
1200	------	28.2	25.7

Table 3.1-2 Melting Point[2], Al, Fe and Si

	Aluminum Al	Iron Fe	Silicon Si
Melting point K	933.5	1810	1685

As shown in Table 3.1-2, however, aluminum which has a low melting point is inapplicable to the thermal storage unit whose temperature will rise up to approximately 1,200K.

In System 1, therefore, an iron material is to be used as the heat transfer medium. This, however, would inevitably be considered very poor from the viewpoint of heat transfer efficiency. This has remarkably reduced the possibility that System 1 may be economically feasible.

To raise the heat transfer efficiency, moreover, it is considered necessary to treat both regolith blocks and iron material on the surface as smoothly as possible so that their contact area will be maximized. It will be difficult, however, to perform such an accuracy-demanding operation on the moon.

System 2 is of such type as to use the sandy regolith in its natural state as the thermal storage element. And the nitrogen gas or helium gas which is reportedly contained most in the overburden of the moon is to be used to transfer the heat. In the heat collector unit, the gas is heated and the hot gas is circulated through the sandy regolith so that the heat will be transferred to and stored in the regolith.

Such mechanical parts as a pump, etc. will be considered for circulating the gas. If there are difficulties involved in manufacturing them on the moon, the mechanical parts may be transported from the earth.

To use a gas, some means should be used to make a hermetically sealed space. If the regolith under the ground is solidified like a wall by use of a thermite reaction, it will be possible to construct the hermetically sealed space without having to dig the regolith. This system, moreover, does not require regolith blocks to be made.

From these points of view, System 2 may be deemed simplest as a construction method among the systems herein studied. Since the gas is circulating, however, the sandy regolith swirls up and adheres to the wall surface of the pipes through which the gas is circulating, and to the interior of the pump. And this would probably prevent the power generator system from functioning properly.

System 3 is to employ regolith blocks as the thermal storage element like in System 1 and nitrogen as the heat transfer medium like in System 2. Regolith blocks are arranged at appropriate intervals in the hermetically sealed space provided under the ground of the moon. The nitrogen gas whose temperature has risen by being heated in the heat collector unit is made to circulate through the hermetically sealed space by means of a pump so that the heat will be transferred to and stored in the regolith blocks.

System 3 would eliminate the necessity of applying an iron material of low thermal conductivity as in System 1, and the possibility that the sandy regolith may affect the gas circulating route as in System 2. Nevertheless, System 3 involves some structural problems such as requiring a large amount of regolith blocks, creating the space for an arrangement of thermal storage units on the moon and treating the space so that the gas does not leak. Nevertheless, this system may be deemed the most feasible among the systems studied as reported herein.

3.1.2 System Heat Balance and Heat Loss

Fig. 3.1-6 shows the energy flow, through which thermal energy is converted to electricity in the glass ocean power generator system, based on a solar beam heat energy input.

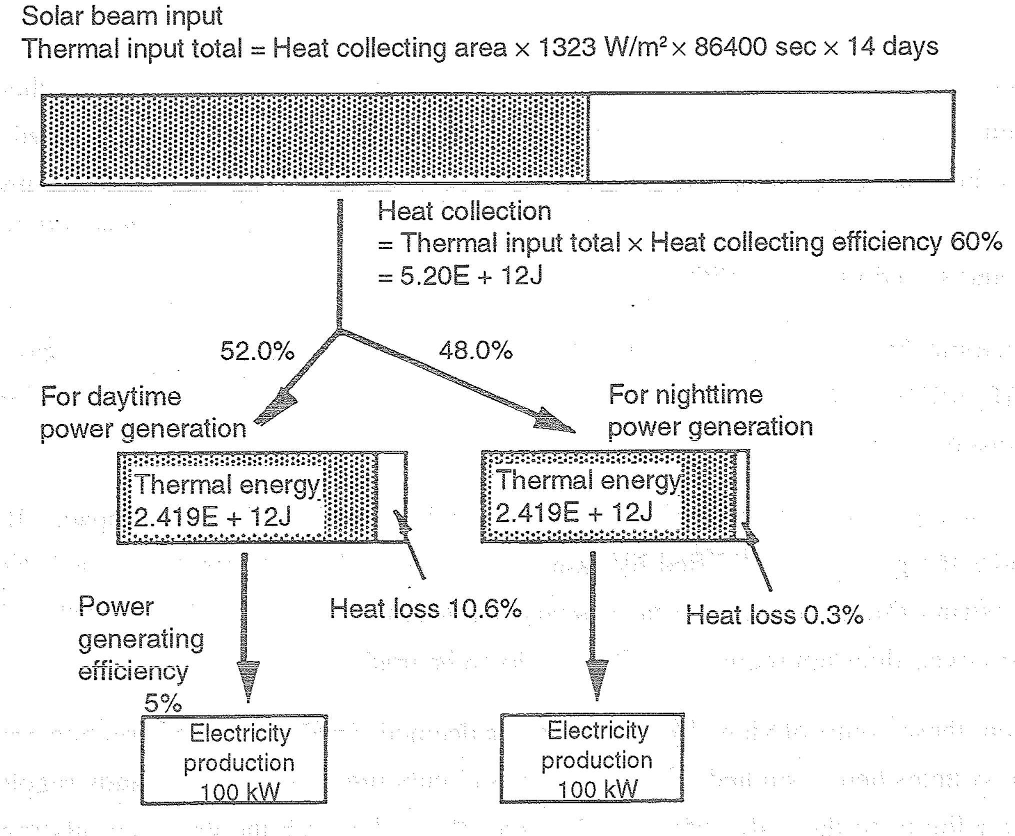


Fig. 3.1-6 Energy Flow

This energy flow has been herein studied on the following prerequisites:

- Generate electricity in equal quantities both day and night.
- Generate 100kW both day and night.
- In the daytime, generate electricity with 50% of the solar beam heat energy input, while storing the remaining 50% in the thermal storage unit.

- In the nighttime, generate electricity, using the heat stored in the thermal storage unit.
- Set both thermal storage unit and piping to a heat loss of 10% on the total heat loss in the daytime and 0.1% in the nighttime.
- Solar beam heat input density: 1,323W/m^2
- Heat collector efficiency: 60%
- Power generating efficiency: 5%

To generate 100kW of electricity day and night for a period of 14 days, a total thermal energy is required as indicated below. From this energy, the nighttime power generating portion is stored in the thermal storage unit and consumed to generate electricity in the daytime.

The thermal energy required to generate 100kW of electricity for 14 days:

$= \text{electricity production} \times 14 \text{ days} \times 24 \text{ hours} \times 3{,}600 \text{ sec./power generating efficiency}$

$= 100 \times 10^3 \text{W} \times 14 \times 86{,}400/0.05$

$= 2.4192 \times 10^{12} \text{J}$ (3.1-1)

The thermal energy which must be collected in the solar beam heat collector, therefore, may be calculated as follows:

Thermal energy collected in a solar beam heat collector:

$= \text{thermal energy to generate 100kW of electricity}/(1 - \text{daytime heat loss})$

$+ \text{thermal energy to generate 100kW of electricity}/(1 - \text{nighttime heat loss})$

$= 2.4192 \times 10^{12}\text{J}/(1 - 0.106) + 2.4192 \times 10^{12}\text{J}/(1 - 0.03)$

$= 5.20 \times 10^{12} \text{J}$ (3.1-2)

Of this thermal energy, 52.0% is used to generate electricity in the daytime while the remaining 48% is used to store heat for the nighttime power generation.

Assuming that a heat collecting efficiency of 60% is available, the thermal input collected in the solar beam heat collector is totaled as follows:

Thermal input total:

= thermal energy collected in the solar beam heat collector/heat collecting efficiency

$= 5.20 \times 10^{12}J/0.6 = 8.67 \times 10^{12}J$ (3.1-3)

To collect the thermal input, the heat collector unit area required may be obtained by the following expression:

Heat collector unit area:

= thermal input total/(solar beam heat input density $\times$ 14 days $\times$ 86,400 sec.)

$= 8.67 \times 10^{12}J/(1323 \times 14 \times 86400)$

$= 5.42 \times 10^3 m^2$ (3.1-4)

If the heat collector unit is of circular parabolic type, the circle will have Radius r as follows:

Heat collector unit radius:

= SQRT (heat collector unit area/π)

= SQRT ($5.322 \times 10^3 m^2/\pi$) = 42m

Next, the volume of a glass ocean thermal storage unit required to generate the electricity indicated above is to be obtained.

In a 100kW-class glass ocean power-generating system, Energy Quantity E required to generate electricity for a nighttime of 14 days may be obtained by the following expression:

E = 100kW/0.05 $\times$ 86400 sec. $\times$ 14 days

$= 2.419 \times 10^9 kJ$ (3.1-7)

where 0.05 is the power generating efficiency.

Volume V required as a heat storage unit may be obtained by the following expression:

$$V = \frac{E}{\rho\,(C_H T_H - C_L T_L)} \qquad (3.1\text{-}8)$$

Subscript H : high temperature, L: low temperature.

Where C is the specific heat (kJ/kg/K) of the regolith block equivalent to glass. At Temperature T (K), it may be expressed as follows[3]:

$C = -1.8485 + 1.04741 \times \log(T)$ (3.1-9)

If $T_H = 700^\circ C$, $T_L = 200^\circ C$ and Regolith Block Density $\rho = 2000\ kg/m^3$ (glass equivalent), Volume V may be calculated as follows:

$V = 1{,}520\ m^3$

In other words, the heat stored in the daytime heats the glass ocean up to a temperature of 700°C, which in turn drops to 200°C while generating electricity in the nighttime of 14 days. In this case, the thermal storage unit in the 100kW power generating system requires Volume $V = 1{,}520\ m^2$.

Based on the methodology of System 3, a study will be made about the heat loss in the glass ocean system.

Fig. 3.1-7 shows an image of the 100kW power generator system, based on System 3. Dimensions involved are according to the study already referred to.

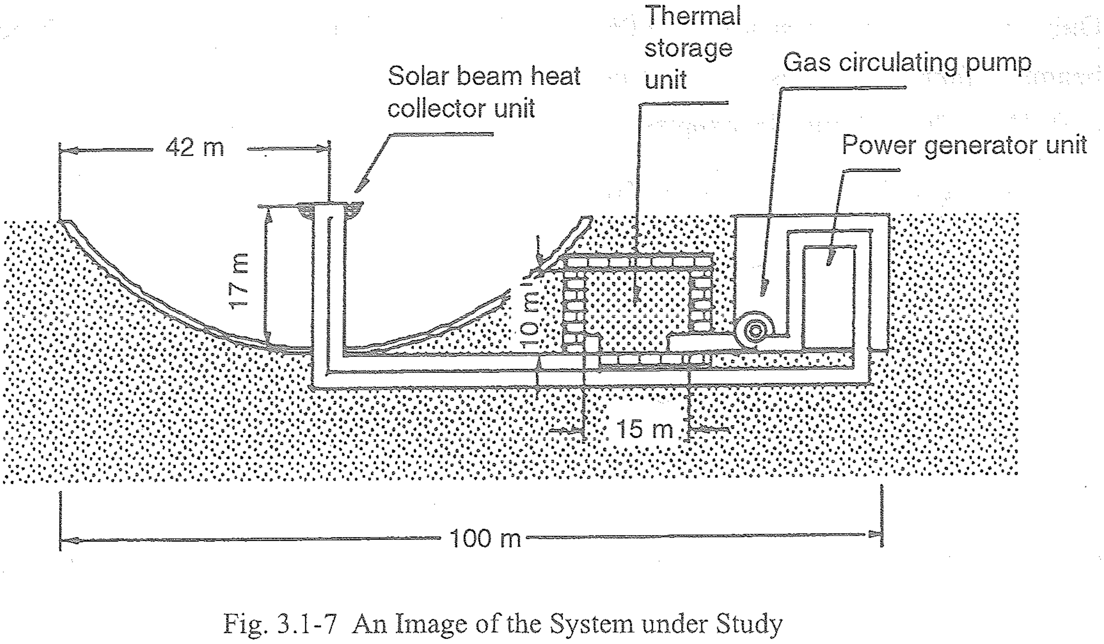


Fig. 3.1-7 An Image of the System under Study

Fig. 3.1-8 shows the relationship between gas-circulating route, thermal input and heat loss while generating electricity in the daytime. In the study made hereunder, the gas-circulating pipe is assumed to have a radius of 5 centimeters.

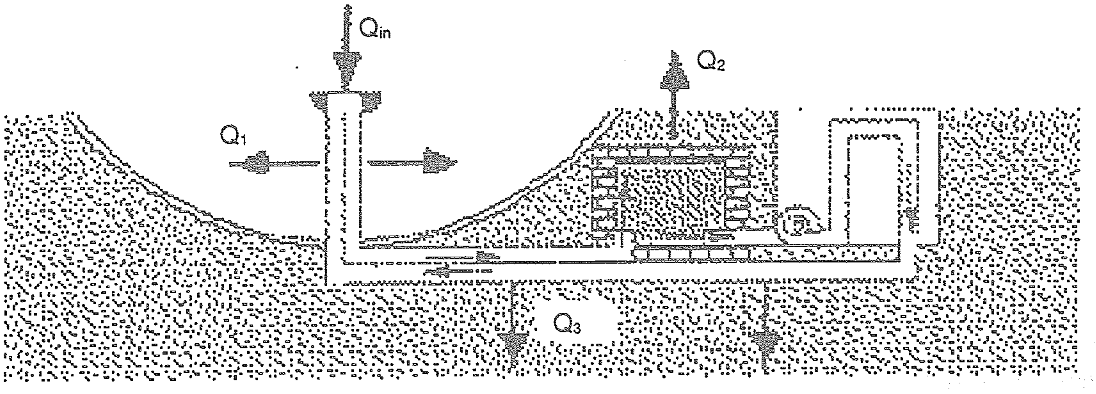


Fig. 3.1-8 Thermal Input and Heat Loss in the Daytime

<Heat Loss in the Daytime>

- Heat Collector Unit's Thermal Input Q_{in}, or a thermal input per unit for a period of 14 days may be obtained as follows:

$$Q_{in} = 2.4 \times 10^{12} \mathrm{J} \qquad (3.1\text{-}10)$$

where it is assumed that the nitrogen gas is heated up to around 800°C.

- Exposed Pipe Portion's Radiation Q_1:

Only radiation towards space (T_2 = 0K) is reckoned while ignoring the input of direct solar beams or their reflections. And the pipe unit is assumed to have a temperature T_1 = 800°C (1,073K). Then, Q_1 may be expressed as follows:

$$Q_1 = A\sigma\varepsilon\left(T_1^4 - T_2^4\right) = 2.0 \times 10^5 \mathrm{W} \qquad (3.1\text{-}11)$$

where A is a surface area of the exposed portion.

$A = 2\pi \times 0.05\mathrm{m} \times 17\mathrm{m} = 5.3\ \mathrm{m}^2$

σ : Stefan-Boltzmann constant

ε : An infrared radiation ratio[4] of quartz glass equivalent at 800°C = 0.5

Radiation Q_1 is totaled at 2.4×10^{11}J for a period of 14 days, which corresponds to 10% of thermal input Q_{in}.

◦ Thermal Storage Unit's Radiation Q_2

The thermal storage unit is hermetically sealed with regolith blocks several tens of centimeters thick on the circumference and surrounded with a highly heat-insulating sandy regolith. If the sandy regolith on the top surface has Thickness d = 1 meter, hermetically sealing blocks have a temperature of 700°C and the ground has a temperature of 100°C, the radiation from the heat collector unit to the ground surface due to the conduction of heat may be expressed as follows:

$$Q_2 = \lambda \frac{\Delta T}{d} A = 900\text{W} \qquad (3.1\text{-}12)$$

where

λ : thermal conductivity of the sandy regolith

= 0.01W/mK

A : area of the heat collector unit on the top surface

= 10 × 15 = 150m²

Under the ground other than the top surface, moreover, A = 650m² and Q = 4,750W, likewise, assuming that the hermetically sealing blocks have a temperature of -30°C in the vicinity of 1 meter on the circumference. And they are totaled at 6.8 × 10^9J for a period of 14 days, which is equivalent to approximately 0.3% of Thermal Input Q_{in}.

◦ Buried Portion's Radiation Q_3

If the temperature is -30°C around twice the pipe diameter, a 100 meter long pipe at 500°C will conduct the heat to the circumference as expressed by the following equation:

$$Q_3 = \frac{2\pi\lambda\Delta T}{\ln(r_2/r_1)} L = 1 \times 10^4\text{W} \qquad (3.1\text{-}13)$$

And it will be totaled at 6.0 × 10^9J for a period of 14 days, which is equivalent to approximately 0.3% of Thermal Input Q_{in}.

From the above, it may be gathered that the heat loss while generating electricity in the daytime is totaled at approximately 10.6% of Thermal Input Q_{in}.

<Heat Loss in the Nighttime>

Next, a study will be made of the heat loss while generating electricity in the nighttime. Fig. 3.1-9 shows the relationship between gas circulating route, thermal input and heat loss while generating electricity in the nighttime. The gas is circulated between thermal storage and heat generating units only in the nighttime and not through the heat collector unit. This mechanism prevents the heat collector unit from losing any heat.

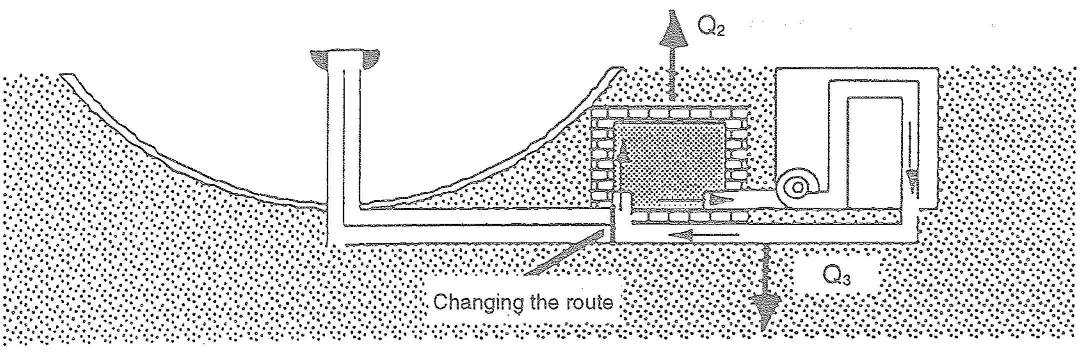


Fig. 3.1-9 Heat Loss in the Nighttime

∘ Thermal Storage Unit's Radiation Q_2

Unlike in the daytime, the ground surface has a temperature of -150°C without any heat supplied by the gas. As a result, the temperature of the regolith blocks in the thermal storage unit is assumed to drop from 700°C to 200°C in 14 days. And the regolith blocks are assumed to have a mean temperature of 350°C. Then, a calculation similar to that under Expression (3.1-12) would result in a radiation of 830W in the upper part of the thermal storage unit and in 3,100W at any portion other than the upper part.

In 14 days, the radiation is totaled at $Q_2 = 4.75 \times 10^9$J, which is equivalent to about 0.2% of Thermal Storage Q_{in}.

∘ Buried Portion's Radiation Q_3

If the pipe has Length L = 50 meters and a temperature of 450°C, we may obtain a radiation of 2,200 watts from the expression (3.1-13). In 14 days, the radiation is totaled at $Q_4 = 2.7 \times 10^9$J, which is equivalent to about 0.1% of Thermal Storage Q_{in}.

From the above, it may be gathered that the heat loss in the nighttime is approximately 0.3% of Thermal Storage Q_{in}.

Thermite reaction is a technology that may be considered available for the structuring of such hermetically sealed spaces as in Systems 2 and 3 under the surface of the moon.

Thermite reaction is a phenomenon of discharging a large amount of reaction heat, with a combustion reaction (oxidation-reduction reaction) propagated instantaneously by giving a thermal stimulus to a mixture of oxides with metal powder (thermite composition mixture).

Table 3.1-3 shows the heat generated and maximum temperature reached by a typical thermite reaction[5].

Table 3.1-3 Heat Generated in a Typical Thermite Reaction and Maximum Temperature Reached at the Heat-generating Portion

Reaction system	$-\Delta H$ (kJ/mol)	Maximum temperature reached (°C)
$Fe_2O_3 + 2Al \rightarrow Al_2O_3 + 2Fe$	832	~3,400
$2/3Fe_2O_3 + Si \rightarrow SiO_2 + 4/3Fe$	323	~2,800
$1/3Fe_2O_3 + Mg \rightarrow MgO + 2/3Fe$	311	~2,300

Silicon, aluminum and iron exist in oxidized form on the moon. It is possible that a thermite composition mixture of silicone or aluminum may be produced on the moon.

If the thermite reaction can be utilized, the temperature available from the reaction will be sufficient to melt the regolith. The thermite composition mixture should be arranged like a bar or string so that it will react continuously. Then, the regoliths adjacent to each other can be molten and solidified, probably allowing for a relatively easy setup of the hermetically sealed space.

References:

(1) HIROTA, Nuclear Power Generation for Space, Japan Society of Mechanics, Report of Achievements in "Subcommittee of Research and Survey into Power Generator Systems and Heat Waste Technologies in Space"

(2) "Thermal Conduction Engineering Data" (1986) edited by the Japan Society of Mechanics

(3) Roger A. Crane, "Evaluation of In-Situ Thermal Energy Storage for Lunar Based Solar Dynamic Systems", NASA-CR-189054 (1991)

(4) "Thermal Conductivity Calculation Techniques", KOHGAKU TOSHO

(5) "Chemistry of Combustion and Synthesis" edited by Combustion and Synthesis Study Group (1992)

3.2 Studying a Subsystem

3.2.1 Thermal Storage Unit

(1) Producing a Sintered Regolith Body

Sintering or melting may be considered available as a method of producing a regolith block as a thermal storage material. Sintering is a lower-temperature process than melting. It does not, however, easily allow us to obtain a highly dense block. As a result, the thermal storage unit composed of a sintered material would lead to a smaller quantity of stored heat per unit volume. In the case of melting, on the other hand, a highly dense block could be obtained. Nevertheless, a hot heat source would be required to produce the block. As the first step in the study, a description will be given about the result of determining the thermal characteristics, with a regolith block made by sintering.

For the raw material, a mixture with a composition similar to that of the regolith (see Fig. 3.2-1) was used. The constituents of the raw material, meanwhile, fall within a range of 100 μm or less in particle diameter as obtained with a sieve. This mixture had been heated at 3 tons/cm^2 and 1,080°C for 5 hours. To subsequently determine the thermal characteristics of this sintered substance, it was fabricated to a diameter of 10mm and a disk-like substance sintered was obtained as shown in Fig. 3.2-2.

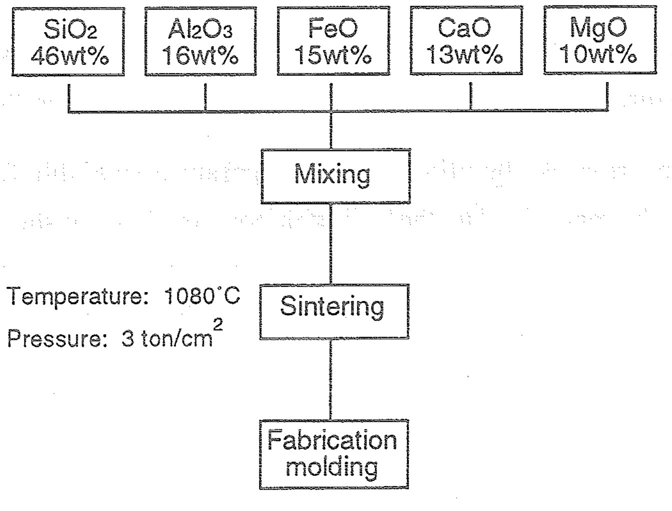


Fig. 3.2-1 Method of Producing a Sintered Regolith Body

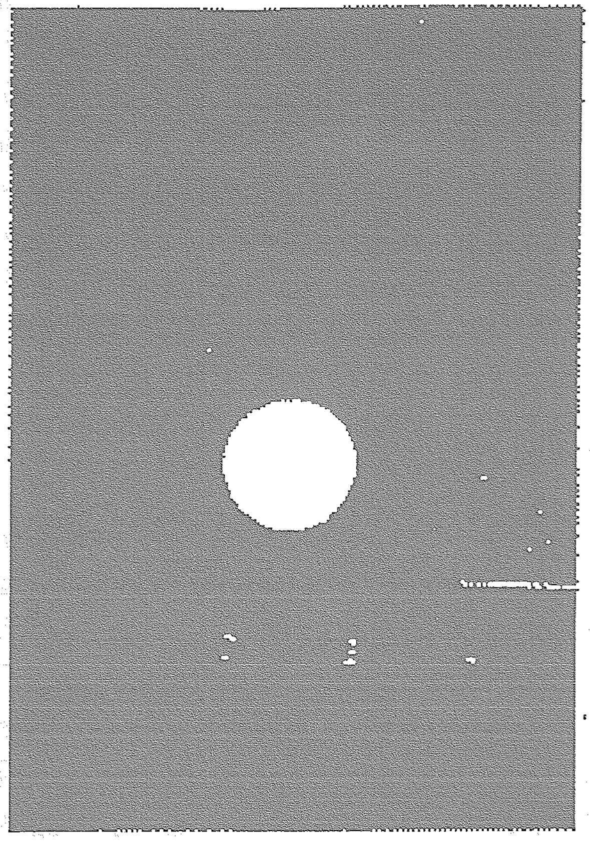


Fig. 3.2-2 External View, Sintered Regolith Substance Trial Manufacture

(2) Measuring Thermal Characteristics

The sintered substance had both its thermal conductivity and specific heat measured by the laser flash method. Table 3.2-1 shows the results of measuring the specific heat and thermal conductivity of the sintered regolith substance trial manufacture. At room temperature, it shows a thermal conductivity of 0.24W/m•K, which is smaller by about one digit than the estimated thermal conductivity (2W/m•K) of the block fabricated by melting. This is presumably because the sintered substance trial manufacture has a low density of about 50%.

Table 3.2-1 Thermal Characteristics of Regolith Substance Sintered

Temperature (°C)	Specific heat J/g • K	Thermal conductivity W/m • K
20	0.51	0.24
640	0.75	0.28

If the thermal conductivity is low in the interior of a thermal storage tank, a problem may occur, that is, a failure to take out the heat within a specified time. Taking this into account, the blocks made by the melting method are considered better. In the future, it is necessary to make a detailed study concerning the thermal performance and production method for blocks made by the melting method. The poor charging level of the sintered substance, however, might be reversely utilized to let a thermal medium pass through the interior. If so, the heat will transfer better. If it is very difficult to make a molten block, therefore, taking the sintering method into account as one of the alternatives will be considered.

(3) Dimensions of Regolith Block

A thermal storage unit composed of blocks would hinder the heat from being transmitted all over the blocks if they were too thick. It is necessary, therefore, to set the blocks to a certain size or smaller. We are still in the stages of studying an outline. It is assumed that the flow of heat inside the blocks is one-dimensional to obtain the dimensions of the block. When the blocks were heated at the lowermost part at 1,000°C for a period of 14 days, their thickness was obtained sufficient to raise the uppermost part temperature from 0°C to the set value. The results are shown in Fig. 3.2-3. A thermal conductivity of 2W/m•K (an estimated physical property value of molten regolith blocks), meanwhile, was used. We know from analysis that the 0.3 thru 1.0 meter thick glass could be heated up to 500 thru 800°C at which a thermal electric conversion is relatively easy.

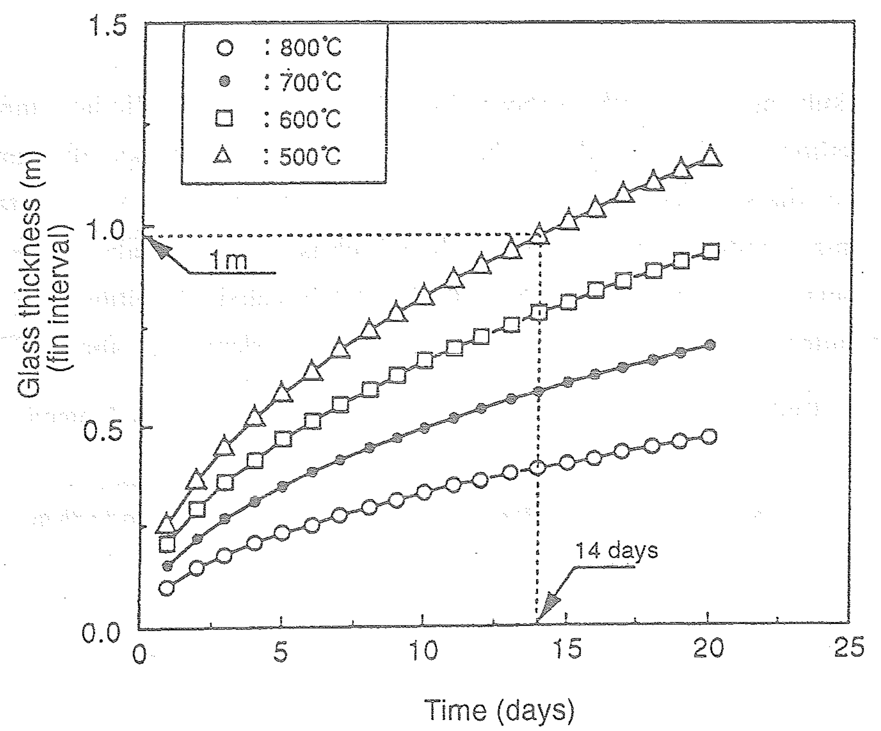


Fig. 3.2-3 Glass Thickness vs. Heating Time/Temperature

3.2.2 Heat Transfer Unit

Fig. 3.2-4 depicts an outline of the lunar energy system. As the medium to carry the thermal energy from the heat collector unit to the thermal storage unit, helium gas or nitrogen gas may be considered as promising candidates, with their availability on the moon and pipe corrosiveness taken into consideration. In other words, a certain sufficiently broad area would be generally required to transfer a constant quantity of heat from a solid to a gas (without including a condensation/evaporation process) since it would involve a low thermal conductivity. To obtain a high temperature by collecting the heat, on the other hand, it would be necessary to minimize the heating portion size. Whether or not a design point or technology could be found to meet both contradictory requirements will be an important point in the future.

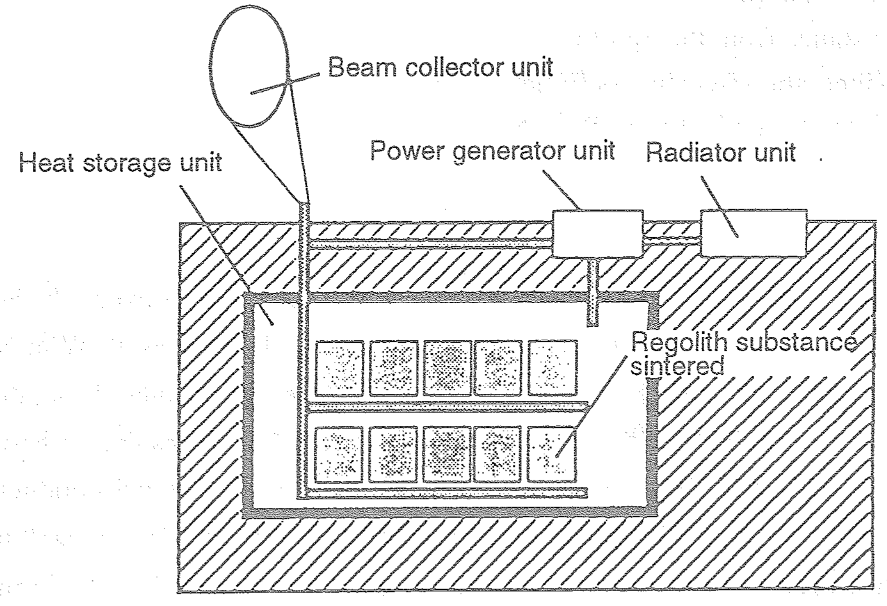


Fig. 3.2-4 Outline of Lunar Energy System

The thermal conductivity problem is important for either the power generator or the radiator unit. The lower the thermal conductivity, the larger heat transfer area will be required to transport a constant quantity of heat. Or if a specified quantity of heat should be transferred under the condition of a limited heat transfer area, a significant difference in temperature will arise on the heat transfer surface. As a result, a lower difference in temperature will arise in the power generator, leading to a decrease in power-generating efficiency.

When the power generator has a temperature fall within the range of room temperature thru 200°C on the cold side, a liquid thermal medium (e.g. water, liquid sodium, etc.) is applicable. Since the thermal conductivity is larger between liquid and solid than between gas and solid, the power generator with a liquid medium applied can be smaller than that with a gas medium applied.

As an equation to calculate the mean thermal conductivity, based on a turbulence, the following expression is known:

$$\alpha_m = 0.037 \times Pr^{2/3} Re^{0.8} \lambda / l$$

where

α_m : Mean thermal conductivity (W/(m^{2}K))
Pr : Prandtle number (-)
Re : Reynolds number (= Ux/μ)
U : Flow rate (m/s)
x : Distance from the tip of flat plate (m)
μ : Kinematic viscosity coefficient (m^2/s)
λ : Thermal conductivity (W/m·K)
l : Flat plate length (m)

If the flat plate is 2 meter long, for example, the thermal conductivity between the helium gas flowing at a current velocity of 20 m/s and the plate may be obtained as 47 W/m^{2}K at room temperature by the expression given above. In the case of water, on the other hand, the thermal conductivity reaches 4×10^4W/m^{2}K, which is approximately 850 times that of helium. The power generator unit has most of its dimensions governed by the thermal conductivity. In other words, the less the thermal conductivity, the larger the heat transfer unit will be. In the case of water, however, it is necessary to carry the medium from the earth in the form of water or hydrogen. Since the quantity to be carried from the earth is not yet known at present, it is impossible to select a thermal medium. It will be necessary in the future to select an optimum thermal medium after studying the weight of thermal media, structures, etc.

3.2.3 Power Generator Unit

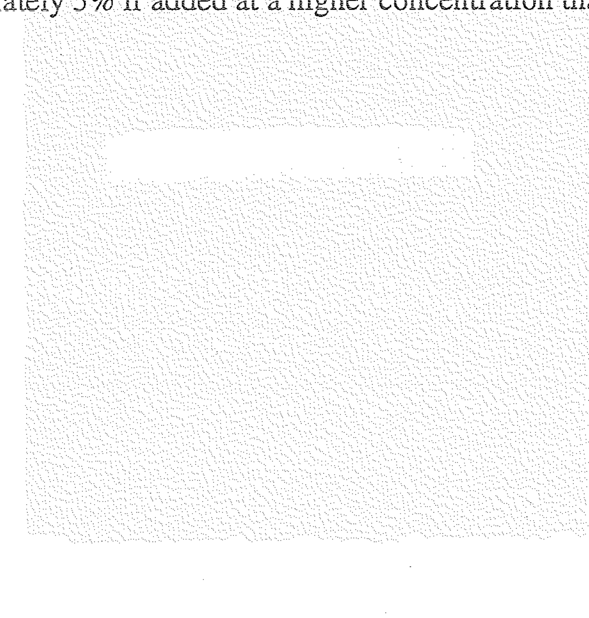
(1) Generating Electricity with Thermal Electric Element

A thermal electric element has been often applied in combination with a radioactive isotope (RI) or the like on a field-proven basis. Nevertheless, it has shown an efficiency level as low as 0.05 thru 0.1. As a result, applications of the thermal electric element have so far been planet surveyor satellites, military satellites, etc. To increase the efficiency of a thermal electric element to a higher level, it is necessary to raise its heat resistance and to improve its Performance

Index Z. At present, an Si-Ge thermal electric element is known as a high-temperature type, and Fe-Si, Pb-Te and Mg-Ge thermal electrons as medium/low-temperature types.

(2) Fe-Si Thermal Electric Element

Thermal electric elements are generally insensitive to purity. Their production, therefore, does not require an advanced purity control system. In addition, the sintering method may be used to produce the thermal electric element, which can in turn be produced in large quantities through a simple production process. An Fe-Si thermal electric element, mainly composed of Fe and Si, both abundantly available in the regolith, has the possibility of establishing a self-proliferative power generating system on the moon. As the first step to verify its feasibility, therefore, the method shown in Fig. 3.2-5 has been used to produce the Fe-Si thermal electric element, whose characteristics have been in turn examined. Fe, Si and a dopant, Al, were used as raw materials. After being melted, the raw materials were purverlized, mixed and sintered into a thermal electric element. Fig. 3.2-6 shows an external view of the element trial manufacture. This element had a working temperature range (hot side) of 500 thru 900°C. With a temperature difference of 500°C between hot and cold sides, the thermal electric element showed a power generating efficiency level of about 3%. In the experiment reported herein, aluminum was set to a quantity of 0.3 atomic%, which, however, could not be considered always optimum but remains a subject for future study. According to the results of testing carried out so far, the iron silicide with aluminum mixed had characteristics resembling those of cobalt or chrome added at low concentrations. Since cobalt or chrome must be added at a higher concentration to maximize efficiency, aluminum is thought to achieve an efficiency level of approximately 5% if added at a higher concentration than the present level.



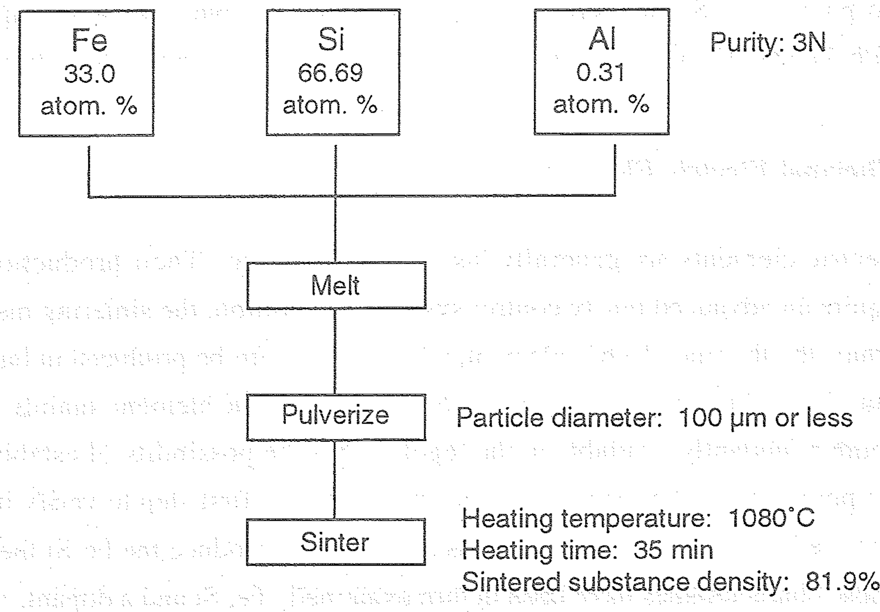


Fig. 3.2-5 Fe-Si Thermal Electric Element Production Method

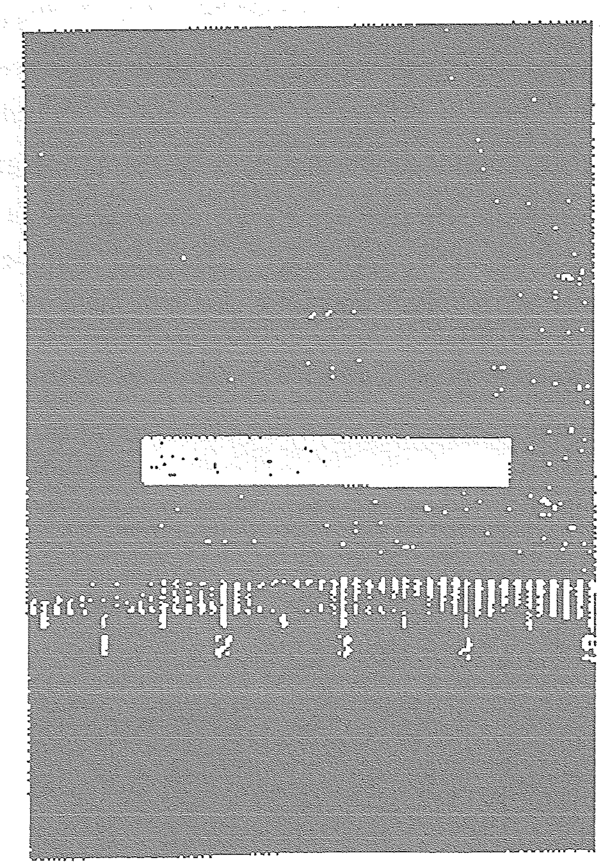


Fig. 3.2-6 Appearance, Element Trial Manufactured

(3) Power Generator Unit Configuration

The power generator unit employing a thermal electric element may be envisaged in two basic configurations. One has the elements arranged on the circumference of a pipe, through which a thermal medium is flowing, with radiating fins mounted around the elements as shown in Fig. 3.2-7. The other has elements inserted directly into the thermal storage unit as shown in Fig. 3.2-8 so that the electricity will be generated by the temperature difference between the thermal storage unit and the electrode side which gets colder due to radiation.

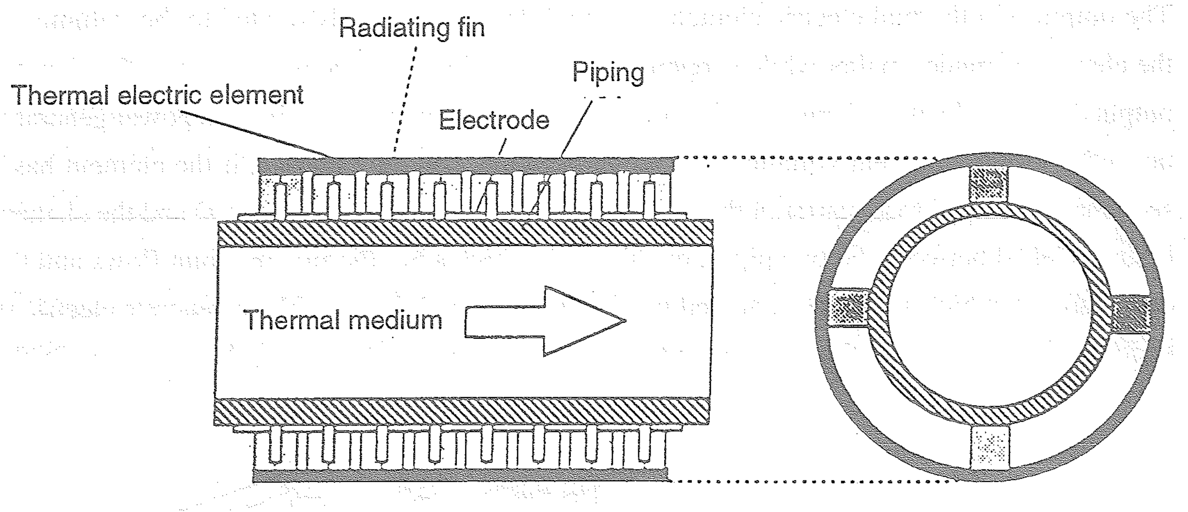


Fig. 3.2-7 Power Generator Unit Configuration

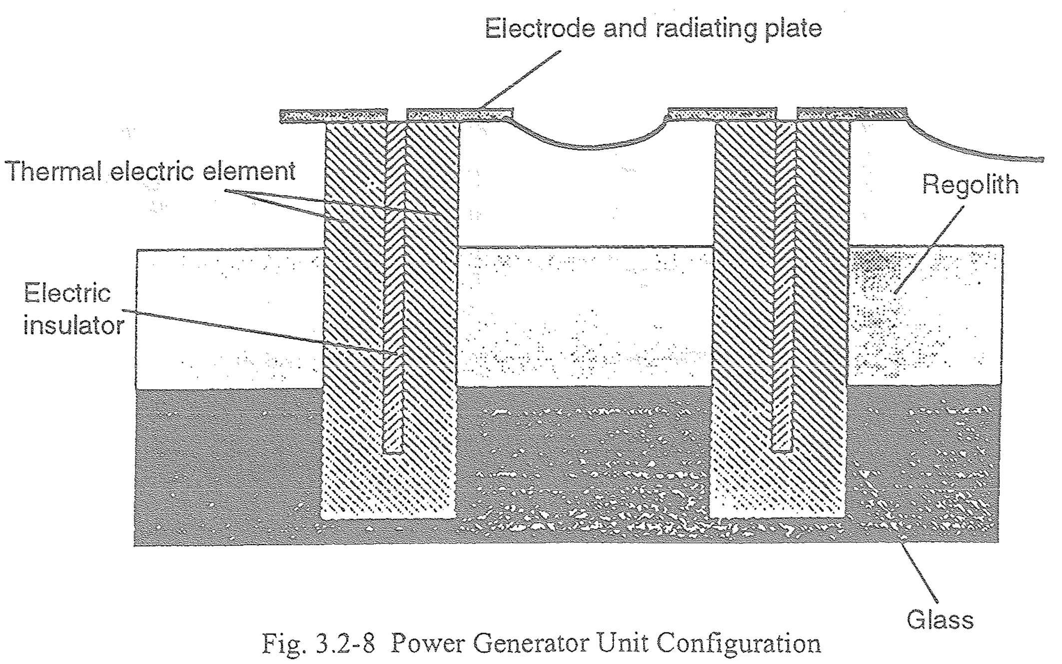


Fig. 3.2-8 Power Generator Unit Configuration

For the former, a 7 centimeter long radiating plate was used, with a thermal input of 2W assumed to enter the element. And the temperature of this radiating plate was analyzed. As a result, the thermal electric element was found to have a temperature difference of 440°C at a radiating plate temperature of approximately 360°C. Thus, it could be gathered that an efficiency level of 2% and an output density of $0.09W/m^2$ are available in the configuration shown in Fig. 3.2-7. For the latter case, similar calculations have been made. Since the element is long, however, only a small thermal input is available so that the output per unit sectional area is found to be as small as $0.01W/cm^2$. The configuration shown in Fig. 3.2-8, therefore, is considered to be not very feasible as a power generator.

The output of a thermal electric element, meanwhile, is not directly related to the volume. If the element is made smaller while keeping both sectional area and length constant, the element output does not change. Using this characteristic would allow us to configure a power generator unit with a small element volume. As shown in Fig. 3.2-9, for example, if the element has a sectional area equal to a quarter of the endothermic plate's (or radiating plate's) and the element is sandwiched between the two pipes, one through which a hot thermal medium flows and the other through which a cold thermal medium flows, then it will be possible to generate electricity (refer to Fig. 3.2-10). In this case, an output density of approximately $0.36W/cm^2$ is available.

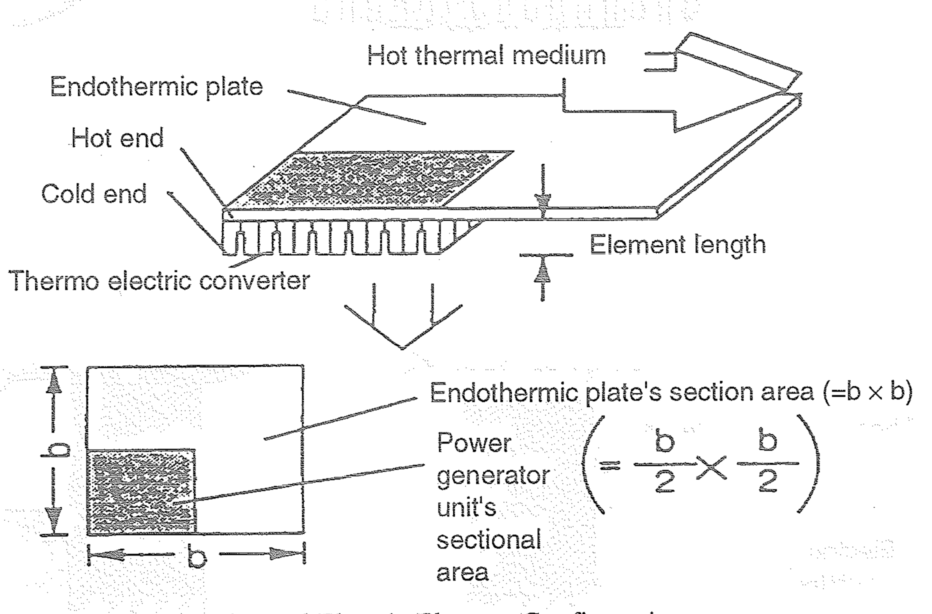


Fig. 3.2-9 Thermal Electric Element Configuration

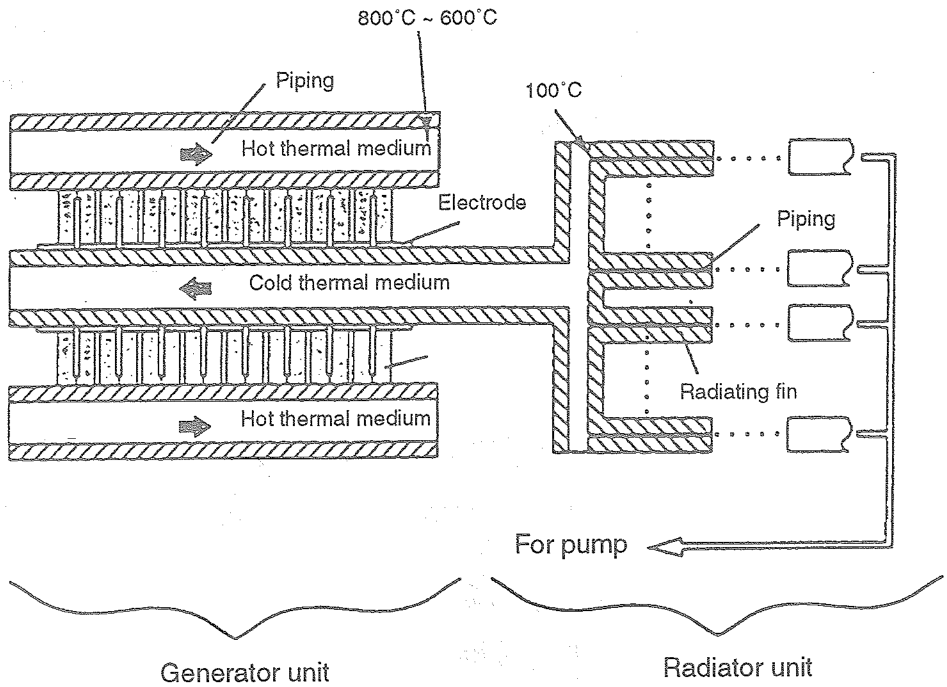


Fig. 3.2-10 Configurations, Power Generator/Radiator Units

(4) Thermionic Conversion and Alkaline Metal Thermal Electric Conversion (AMTEC)

To generate electricity with thermal electrons, a very high temperature (21,750 thru 2,000K) is required on the power generation principle that an electromotive force is produced with thermal electrons discharged. And it is necessary to keep the thermal storage unit at a temperature higher than that. Thermionic conversion, therefore, is considered to have a low feasibility.

The alkaline metal thermal electric conversion (AMTEC), on the other hand, can be expected to operate at an efficiency level of 0.15 thru 0.35 equivalent to but at a lower operating temperature (1,000 thru 1,350K) than thermionic conversion. Thus, the AMTEC has a possibility of being applied to solar thermal electric power generation. Its basic configuration and power-generating principles are described below.

The AMTEC has a power generator unit constructed so that the beta-alumina is sandwiched by hot and cold areas as shown in Fig. 3.2-11. In the hot area, liquid Na is heated at 900 thru 1,300K while a porous electrode is placed in contact with the beta-alumina in the cold area. In addition, a condensing wall which is cooled down to 400 thru 800K is arranged by way of a vacuum layer. The beta-alumina is electrically conductive to cations of Na while remaining an insulator to electrons. As a result, hot Na discharges electrons on the surface of the solid electrolyte and passes through the beta-alumina, using as the driving force the Na steam pressure difference between hot and cold areas of the Na cations. Consequently, the hot Na reaches the difference between hot and cold areas of the Na cations. Consequently, the hot Na reaches the surface of the beta-alumina on the cold side. Those electrons which have passed through an external electric circuit, leaving the liquid Na in the hot area, neutralize the cations of Na on the interface of the porous electrode with the beta-alumina. The Na so neutralized absorbs the evaporation heat while dispersing in the porous electrode. The Na which has evaporated passes through the vacuum layer and condenses on the cold condensing wall. The liquid Na so condensed is returned to the hot area by means of an electromagnetic pump.

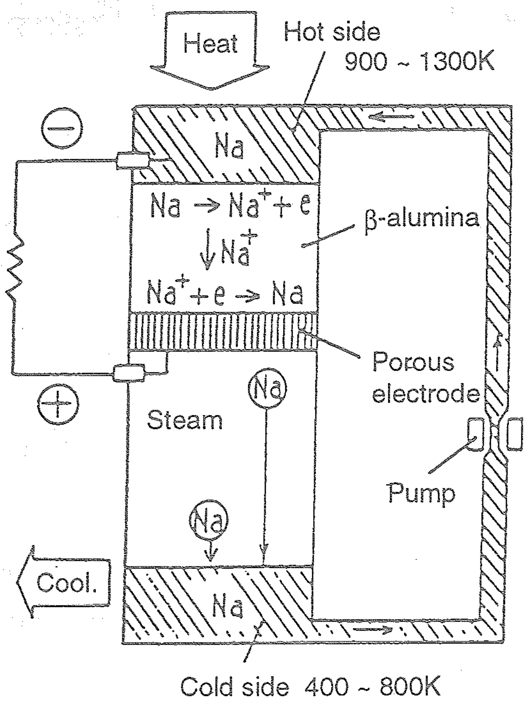


Fig. 3.2-11 Basic Configuration, AMTEC

The AMTEC has the following features:

(1) It is a direct power generating system in which heat is directly converted to electricity.

(2) It can be expected to show a high level of power generating efficiency (up to 35%) for a direct power generator system.

(3) The waste heat has a relatively high temperature (400K thru 700K).

The AMTEC has various advantages as referred to above. To materialize an AMTEC system, however, there are some technologically important challenges awaiting a solution. The AMTEC, for example, has an efficiency level of around ten or more percent. To increase the efficiency, it is necessary either to reduce the ion resistivity of the beta-alumina or to develop a thin and strong beta-alumina. It has been so far energetically developed as an electrolyte for Na/S cells. And the beta-alumina has had its characteristics clarified around an Na/S cell operating temperature of 350°C (623K). Over an AMTEC operating temperature range of 900 thru 1,300K, however, there are many unknown factors, such as strength, coexistence with Na, cause and effect relations between impurities, such as potassium, calcium, etc. and rupture of the beta-alumina, an increase in resistivity, etc. And all of them have remained challenges to be met in order to achieve a high level of efficiency.

Those Na ions which have passed through the beta-alumina are coupled with electrons from an external circuit on the interface with the porous electrode. And the Na neutralized obtains the evaporation heat to evaporate while dispersing in the porous electrode. It should, therefore, preferably have such characteristics as low electric resistance, especially low resistance to the passage of evaporated Na steam. To this end, electrodes of various construction have until now been proposed. Nevertheless, no definitive one has been selected yet while their long-term stability has hardly been verified. From now on, the development of an electrode which excels in durability and stability while showing a low level of resistance is required.

3.2.4 Radiator Unit

Fig. 3.2-12 shows a configuration of the radiator unit. The thermal medium to cool down a thermal electric element, for example, is cooled down while being made to pass through the radiating fins. After that, it is sent to a pump, thereby cooling down the thermal electric element. Now, let's assume that the fin is 1 meter long and it has an inlet temperature of 300°C and an outlet temperature of 200°C. With the radiator plate in Fig. 3.2-13 assumed, its temperature distribution could be given by the equation given below.

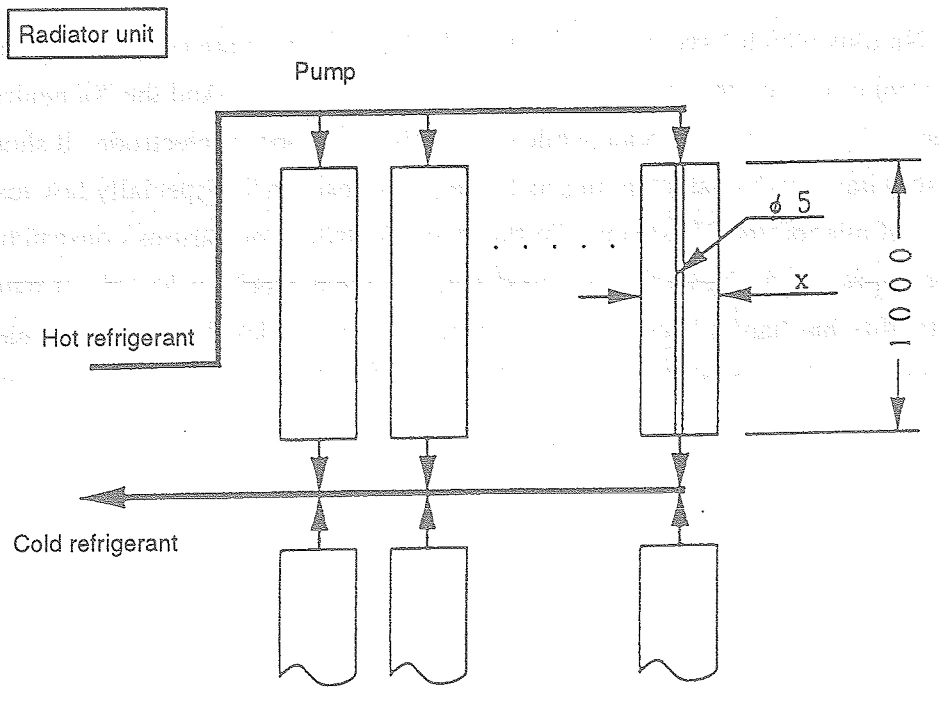


Fig. 3.2-12 Configuration, Radiator Unit

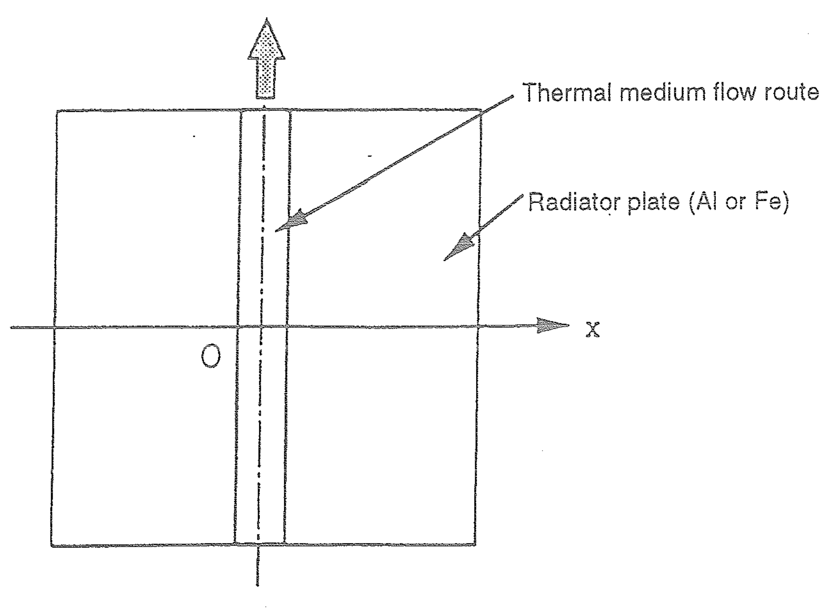


Fig. 3.2-13 Analytical Architecture

$$T/T_0 = (1 / (1+0.9487 \cdot X \cdot A \cdot (T_0 / 1000)^3)^{2/3}$$

$$A = (\sigma \cdot \varepsilon \times 10^9 / \lambda p / tp)^{1/2}$$

σ : Stefan-Boltzmann constant ($5.67 \times 10^{-8} W/m^2/K^4$)
e : Radiation ratio (-)
λ_p : Panel's thermal conductivity (W/m·K)
t_p : Thickness of panel (m)
T : Temperature at x (K)
T_0 : Temperature with x = 0 (K)
X : Position rectangular to a path of flow (m)

If the radiator plate is made of aluminum ($\lambda = 235$W/m·K), has Radiation Ratio $\varepsilon = 0.8$ and is 1mm thick, it will have an x-axial temperature distribution as shown in Fig. 3.2-14. To strictly obtain the radiation, it is necessary to integrate the radiations by point on the radiator plate. Since it is still in the rough study stages, however, the radiation has been obtained, with the radiator plate's temperature represented by the value at a point on Line x.

To radiate on a 100mm wide (50mm on one side) radiator plate, for example, an area of $0.34m^2$ per kilowatt is required if T_{p1} (503K) is taken for the representative temperature. And a 200mm wide (100mm on one side) radiator plate requires an area of $0.40m^2$ if T_{p2} (485K) is reckoned as the typical temperature. If the radiator plate allows for radiation on both face and back, 1.7 pieces of the radiator plate will be required to radiate 1 kW in the former case and 1 piece in the latter case.

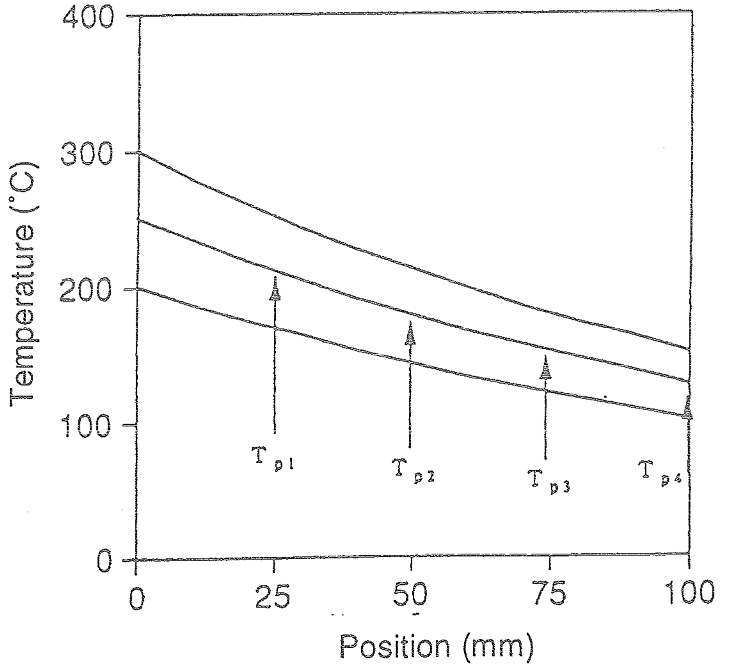


Fig. 3.2-14 Temperature Distribution, Radiator Plate

Generally, the denser an arrangement of the thermal medium flow route, the more uniformly the temperature will be distributed on the radiator plate and the less the radiating efficiency will decrease. Nevertheless, an increase will inevitably arise in the man-hours required to make and connect the thermal medium flow route (piping) and the radiator plate. If all of them can be produced on the moon, no problem will arise. If a certain amount of materials needs to be carried from the earth to construct the radiating system on the moon, it may be considered as one of the important challenges to analyze some optimum points (radiator plate dimensions, radiating temperature, etc.).

3.3 Problems and Challenges

The glass ocean 100kW-class power-generating system involves problems and challenges as indicated below.

(1) Concept

- The glass ocean system is based on the concept that it must make the most effective use of lunar resources. Especially in the initial stages, however, a large amount of materials has to be hauled from the earth, thereby raising the problem of high total cost. It is necessary to allow for a quantitative evaluation of the system by studying the energy pay-back time through a prolongation of service life and the secure obtainment of self-proliferativity.
- Estimate the weight of haulage from the earth, strive to reduce the weight, and estimate and evaluate the construction cost. All of these factors will turn out to be keys to the success in the materialization of the system. In addition, it is also necessary to study the system extensibility, including system design on a unit by unit basis, etc.
- A positive operation is required to select the daytime or nighttime power generating system (to switch the thermal flow). In this case, it may lead to a problem of a decrease in electricity production capacity. It is necessary, therefore, to study a variety of kinds of control.

(2) Overall System

- The study made in the current fiscal year has extracted a low level of the overall system efficiency, raising a significant problem. It may be deemed as the serious challenge to the improvement of the efficiency of the various subsystems in the entire system.
- There is a fear that exposed portions may suffer from radioactivity. The effects of radioactivity on the system have not been studied in the current fiscal year. It will be necessary to take countermeasures having understood the moon's environment.
- Concerning the numerical physical properties relating to the regolith, which should turn out to be the basis of the system performance of the glass ocean system, a sufficient amount of data is not available. In the current fiscal year, assumed values have been used, based on a variety of assumptions. In this respect, it is urgently necessary to take actual measurements by the use of a simulation regolith or the like so as to obtain highly reliable data.

- Labor and gravity are required to construct structures which are capable of withstanding a difference in pressure when using a gas. It is necessary to obtain strength data concerning the structural materials which are to be made of regolith.
- The system will be exposed to remarkable differences in temperature, especially between daytime and nighttime. A thermal strain or the like may turn problematical in the system. These factors should be evaluated by the use of a thermal model. At the same time, their effects on electronic equipment, etc. should be fully studied and examined.

(3) Power Generator Unit

- The existing system is less efficient than a solar cell. An increase in efficiency of the equipment including a thermo electric converter is the greatest challenge awaiting solution. It will also be a study project to make a thermal electric element on the moon, to prolong its service life, and so on.
- A method of interconnecting thermal electric elements (either mechanical or electrical) would be complicated. This splice would significantly affect the capacity of a power generator unit. It is necessary, therefore, to study and establish a simple and secure interconnection method.
- It is necessary to study the equipment and techniques to stabilize the electricity generated.

(4) Heat Storage Unit

- When the heat storage unit performance is evaluated at its maximum limit, a high temperature of 2,000°C is available. It is difficult, however, to secure a material capable of withstanding such a high temperature. It is necessary to clarify the temperature obtainable as well as the construction of a heating medium.
- It is necessary to achieve the accuracy required for the surface of a solar beam collector mirror, especially based on lunar resources.
- A beam collector without a driving system would fail to collect a sufficient quantity of heat. Tracking the sun would make the system too complex. It is a challenge to establish the simplest and most efficient heat collector system, including the structure of its parts.

(5) Heat Transfer Unit

- It is generally difficult to evaluate heat transfer with a gas. In the current fiscal year, a very simple model only has been used to make the evaluation. It is necessary to make an analysis, with more detailed models prepared to cover the heat transfer capacity, thermal leakage to piping, etc.

- There is no water on the moon. It is impossible, therefore, to construct a very simple and highly efficient heat transfer system on the moon, using water like on the earth. A highly efficient heat transfer system must be built there, with consideration given to the availability of resources and to performance, etc.
- Using a fluid as the thermal medium will invoke pump haulage and construction problems. It is necessary to clarify the conceptions, specifications and/or other requirements for a pump suitable for the glass ocean system.
- To prevent the heat from leaking out of the heat collector unit in the nighttime, a heat transfer rough selector mechanism will be required. It is necessary to study a simple mechanism capable of securely selecting an appropriate heat transfer route.

(6) Heat Storage Unit

- Once a block type heat storage unit has been selected, it will be difficult to melt and solidify its materials into blocks (including a thermal control to eliminate cracks, etc.). It is necessary to acquire the technology for producing molten blocks through a characteristic test by the use of a simulant.
- With a gas applied as the thermal medium, a large amount of resources and energy will be required to construct a hermetically seal space. Some energy-saving ideas such as thermite reaction methods or the like, will be called upon to be embodied more and more.

(7) Radiator Unit

- In current studies, a thermal flow has been obtained by radiating the stored heat into space. Especially in the nighttime, the heat is important. It is necessary, therefore, to study a system concept which could be coupled with the use of heat.

(8) Operation, Maintenance and Reliability

- The glass ocean system is to use regolith as a heat insulator. A variety of subsystems, including the heat storage unit, are to be arranged under the ground. From a system maintenance point of view, a buried portion, if any, would turn out to be a negative factor. Buried portions should be built in a maintenance-free system as far as practicable. At the same time, it is necessary to study a system layout which would allow for any necessary maintenance operation and/or replacement.

- It is necessary to analyze the reliability (failure) at a subsystem and/or component level, with consideration given to the environment on the moon, such as radioactivity, meteorites, temperatures, etc., so as to clarify the service life and/or maintenance/replacement cycles, and the like. With every failure mode of the system as a whole taken into consideration, it is necessary to make a system reliability analysis, such as FTA, FMEA, etc. so as to establish an appropriate monitoring system and/or a suitable maintenance policy.

4. Studying a 5GW-Class Power Generating System

4.1 Studying a System Configuration

On the assumption that the 100kW-class power generating system studied in Section 3 is to be combined into a 5GW-class power generating system to transmit energy to the earth, a study is to be made concerning the system size.

The term, 5GW-class power generating system, as used herein, means a system which has the capacity to transmit an energy of 5GW to the earth. The energy transmission efficiency is to be detailed in the achievement report to be prepared by the Energy Transmission Subcommittee. Nevertheless, it is estimated at about 50%. A 5GW-class power generating system, therefore, is required to generate about 10GW of electricity, in reality.

For generating 10GW of electricity, one hundred thousand units of the 100kW class power generating system are required. As shown in 3.1, a circle with a radius of about 42 meters is the size required for a heat collector unit in the 100kW-class power generating system. With sizes of heat storage and power generator units taken into consideration, it may be assumed that one 100kW-class power generating system is installable within the equilateral hexagon in which a circle with a diameter of 100 meters is inscribed. Then, the overall layout of the 5GW-class power generating system is to be studied.

According to a study made by the Energy Transmission Subcommittee, the 5GW-class transmission system requires a transmitter with an extension of 10 kilometers in diameter. And it is considered efficient for a series of power generating systems to be located so as to surround the transmitter.

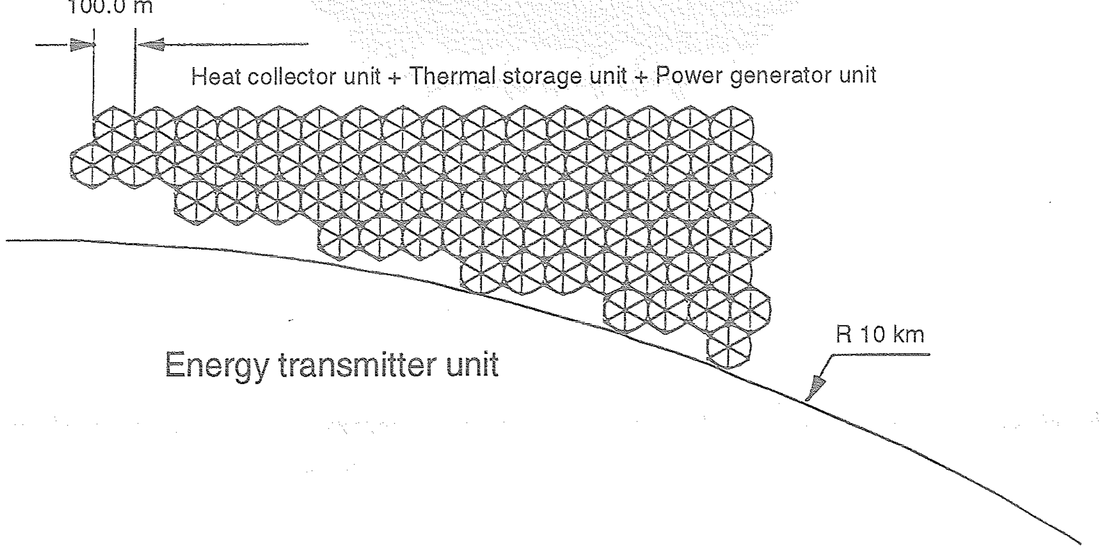


Fig. 4.1-1 Layout, Glass Ocean

It has been assumed that the 100kW-class power generating system is installable within the equilateral hexagon in which a ø100m circle is inscribed. In this case, the equilateral hexagon has sides 57.7 meters long. And it is assumed that such a hexagon is to be laid out without any gaps around the ø10km transmission system. Fig. 4.1-1 shows a partially extended image of the glass ocean so laid out.

One hexagon has an area of:

$$(57.7 \times 100/2) / 2 \times 6 = 8{,}655 \text{ m}^2$$

One hundred thousand units are required for the glass ocean system. Since it is necessary to provide an identical number of hexagons, the following area will be required as a whole:

$$8{,}655 \times 100{,}000 = 8.655 \times 10^8 \text{ m}^2$$

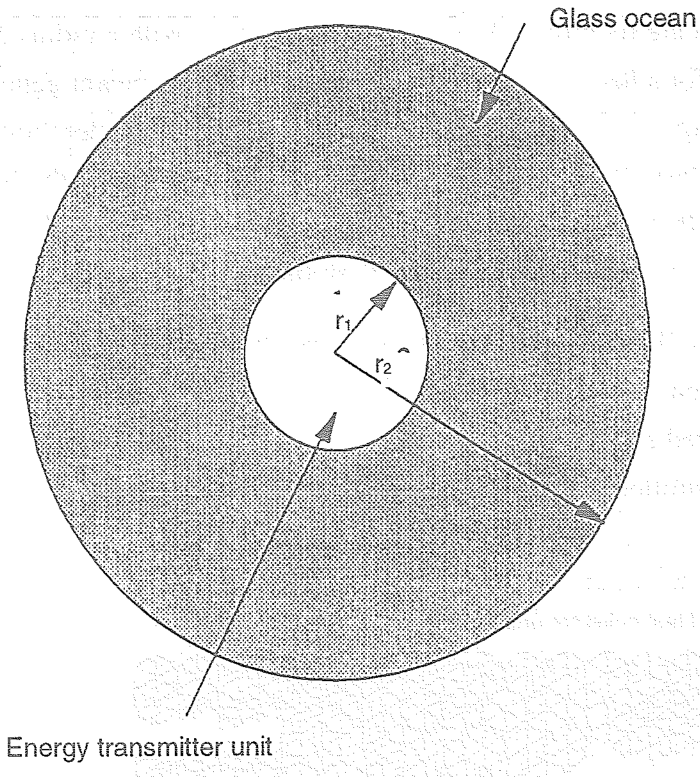


Fig. 4.1-2 Overall Size

If the glass ocean is arranged on the circumference of an energy transmitter unit as shown in Fig. 4.1-2, the shadowed zone relates to the area referred to above.

Therefore, the following equation may be established:

$$\pi r_1^2 - \pi r_2^2 = 8.665 \times 10^8$$

Since $r_1 = 5{,}000$ meters,

$$r_2 = \sqrt{\frac{8.566 \times 10^8}{\pi} + 5000^2}$$
$$= 17253 \text{ m}$$

The system as a whole, therefore, is considered to have a size of approximately 17 kilometers in radius.

4.2 Problems and Challenges

The 5GW-class glass ocean power-generating system intended to transmit its product energy to the earth involves problems and challenges as described below.

(1) Concept

- Coupled with an increase in size, the system will require a prolonged period for its erection while the service life of equipment components and electronic parts will have a significant influence on the energy system feasibility. In addition, the high total cost is likely to require many years to recover the amount of money invested. To maintain an advantageous position over other energy systems, the 5GW-class power-generating system essentially requires a simple and short-term construction method. At the same time, it is absolutely necessary to quantitatively evaluate and improve the service life and reliability level of equipment.
- The cost is likely to increase, considering that the labor required to erect the system on the moon is increasing, resulting in a prolonged stay there. It is necessary to study an unmanned construction by simplifying the process.
- The materials to be hauled from the earth to the moon are too voluminous to be covered by the haulage systems currently available. It is important, therefore, to study a low-cost haulage system which should minimize the haulage from the earth to the moon. As far as the haulage system is concerned, moreover, the existing reliability level of 98% is too inefficient to construct a full-scale haulage system. This point of view needs to be taken into due consideration.
- Extending the system to full scale might significantly alter the environment and/or topographical features of the moon itself. A way of obtaining political understanding is needed.
- If it is intended to transmit electricity to the earth, the 5GW-class power generating system will of course be less economical than a system on the earth. It is necessary to study the energy balance while fully understanding the problems of exhaustion of resources and energy on the earth.

(2) Production relating to the Overall System

- To produce metals out of the regolith, there are the following challenges:
  - To establish a metal refinery process (hydrogen reduction method, and/or molten salt electrolysis).
  - To establish a production process capable of attaining the required level of purity.
  - To make a compact metal refinery.
  - To secure a method of acquiring the catalysts, etc. required in the process of refining metals.
  - To establish an aluminum production method at a low energy cost.

- The gases contained in the regolith are very poorly concentrated, or an immense amount of regolith has to be treated to extract and/or separate gases. It is necessary to establish an image of a small-size gas extraction/separation plant which involves a simple process.
- To make metal materials and parts of the metal constituents, a sufficient level of performance is required to machine a part to its required accuracy. To secure resources (electric power and cooling), cleaning materials, catalysts, etc., it is necessary to make a satisfactory study.
- The thermite reaction on the moon, which is a key technology in constructing the system, needs to be studied concerning its reaction to the lunar environment and to the lunar overburden untreated, etc.
- A realistically feasible production plan is to be mapped out after clarifying the materials to be produced on the moon, including their annual production. In addition, techniques should be studied to integrate parts and so on.

(3) Overall System

- According to the estimates made so far, it has to be said that the system efficiency as a whole is too low. It is a significant challenge to increase and/or improve the efficiency of each subsystem, which holds the key to an efficient system.

(4) Power Generator System

- Coupled with a gigantic increase in electricity production, the power generator unit will have a very large weight, mainly comprising thermal electric elements. It is necessary to establish a method of producing thermal electric elements on the moon, coupled with an increase in their efficiency.

(5) Heat Collector Unit

- The efficiency of existing heat collector units requires too large an area. Coupled with this, it is difficult to produce related structures because a satisfactory performance cannot be secured in the heat transfer zone of a beam collector. It is necessary to study a highly efficient heat collector system and to improve the performance of its heat transfer zone.

(6) Heat Transfer Unit

- An ideal medium does not exist taking into consideration the heat resistance, simplicity, cost, high reliability and availability of resources on the moon. Water, which is an ideal thermal medium on the earth, does not exist on the moon. It is necessary to select an optimum medium and to study how to use the optimum thermal medium.

(7) Radiator Unit

- A mere radiation into space would require equipment of an immense size. Studies made in the current fiscal year have told us that a very immense area next to that for a radiator unit would be required for space radiation. It is necessary to study the optimization of both construction and materials. At the same time, efficient radiation should be studied, too.

(8) Power Transmission System to Transmit Energy

- To transmit electricity, it is necessary to stabilize both voltage and current. To achieve this, a simple stabilizer system would be called upon while the equipment would need be smaller-sized.

(9) System to Transmit Energy to the Earth

- When a microwave power transmission to the earth is envisaged, some problems will be inevitably raised, including an acceleration of global warming, and communication interference and aircraft hazards caused by a highly dense power transmission, etc. The studies made in the current fiscal year have disclosed that a decrease in energy density would allow various faults to be eliminated almost completely. Nevertheless, it is necessary to proceed with the studies on the public acceptance to microwaves, and on the faults in more detail.

(10) Operation, Maintenance and Reliability

- Concerning reliability, a power amplifier has been taken up as an example in the current fiscal year to study the maintenance policy in preparation for an eventual failure. It has been concluded that an optimized policy would allow the system to be maintained properly if 18 pieces of the power amplifier are replaced per hour. This, however, will obviously turn out to be a significant burden even if many control areas are provided. A defective rate of 1000 FIT recently set should be minimized as far as practicable. In addition, a method of allowing for a decline in power should be also studied while bringing about the freedom from maintenance. Thus, there are many problems that still remain unsolved. It is necessary, moreover, to take into consideration the maintenance of controls, cables, etc. in addition to the power amplifier. With these factors taken into account, it is necessary to establish an optimum maintenance policy and/or an optimum maintenance system.

5. Conclusion and Challenges for the Future

Described hereinbefore is a clarification of the new energy system on the moon, called the mare of glass, worked out in the beginning of Fiscal 1994. Based on the two forms,

(1) A 100kW-class power-generating system to support the missions on the moon for the time being, and

(2) A 5GW-class power generating system intended to return the energy to the earth,

a feasibility study has been made about the systems while clarifying related subsystems and trading off a number of ideas.

The studies made in the current fiscal year have clarified the following:

(1) 100kW-Class Power Generating System

Generating approximately 100kW of electricity to support the initial missions on the moon has been found to be nearly feasible with the mare-of-glass system. At the same time, technological challenges essential to the system feasibility and the key points for the success in constructing an efficient system have been extracted. From the viewpoint of a further improvement in system efficiency, moreover, those subsystems which require further study have been also clarified.

In addition, there are a lot of subsystems which still remain merely conceptual without having reached a detailed image. The important points with which we should particularly proceed in our studies have been extracted as follows:

- Construction of a beam collector (heat collector unit),
- Selecting a heat transfer system and a medium,
- Selecting a material from which the mare of glass is to be made, and verifying its thermal storage capacity.

From now on, it is also necessary to proceed with a comparative study with other energy systems on the moon.

(2) 5GW-Class Power Generating System

The 5GW-class power generating system studied in the current fiscal year is intended to return energy to the earth. Its initial sizing has been made in the studies during the current fiscal year. As a result, it is known that the mare of glass (especially the beam collector unit) would have an immense size. In addition, it is forecast that the number of parts required would be so immense as to exceed the order of one hundred million. From these findings, it has been gathered that the future significant challenges include a system construction method with self-proliferativity secured, maintenance, and so on. It is also necessary to make a satisfactory study of the integration with a power transmission system.

Part 2

Energy Transmission Subcommittee

1. Introduction

Today, electricity is largely dependent upon such fossil fuels as petroleum and liquefied natural gas and upon nuclear power. Petroleum and liquefied natural gas, however, have their reserves limited while their prices have been rising. Nuclear power also involves some difficulties in securing safety as typically seen in the accident which took place in Chernobuil. And it has become more and more difficult to newly find nuclear power plant locations. To support the rapidly increasing world population and the developing economic activities all over the world, on the other hand, it is said that there will be a demand for approximately ten times the current energy consumption in 30 years. To overcome this energy crisis, an environmentally-friendly full-scale energy source is essential. A number of environmentally-friendly energy sources have been studied, such as solar cells, fuel cells, wind power, geothermal power, and so on. None of them, however, has turned out yet to be a key power source comparable with thermoelectric or nuclear power. Photovoltaics with solar cells, for example, is a clean power source, which does not emit any carbon dioxide. Nevertheless, it cannot generate electricity in the nighttime and its performance is dependent upon weather conditions. As a result, photovoltaics is insufficient as the key power source which must ensure a stable supply of electricity. At present, photovoltaics is being developed as a distributed power generator system serving on a supplementary basis. If possible, therefore, a key power source should be developed which is capable of taking the place of thermoelectric or nuclear power. As one of the future key power sources, a solar thermal power satellite or a moon power plant is likely to operate so that the electricity generated in space will be transmitted to the earth.

It is no exaggeration to say that success in the materialization of a supply of energy from space to the earth depends upon whether or not a wireless power transmission technology can be successfully developed. It would not pay, due to the immense costs incurred, if the electricity generated in space had to be converted to hydrogen, which had to be in turn conveyed by freight aircraft to the earth. The only way is to transmit the electricity using electromagnetic waves or beams larger than microwaves. Discussed hereunder is the feasibility of wireless power transmission from a moon power station as a power generating system in space.

Studying a feasible supply of electricity from space is naturally subject to the major prerequisite for the conservation of the earth's environment, including living things. The first problem is the effect of power-transmitting microwaves on living things. As a solution to this problem, an extensive power-incoming antenna (rectenna) may be constructed to weaken the microwaves to the level at which they do not adversely affect any living things. In addition, the rectenna should be located remotely in a desert or on the sea far away from the land so that any living things cannot approach it easily. The second problem relates to global warming. As far as global warming is concerned, a supply of electricity from space with microwaves is considered more advantageous than thermoelectric or nuclear power because approximately 90% of the microwaves with which electricity would be transmitted to the earth could be converted to electric power while only the remaining 10% would change into heat. In other words, microwaves allow for a power generating efficiency of 90%. Thermoelectric and nuclear power may be deemed to generate more heat. If the heat produced when the supplied electricity is consumed raises a problem, moreover, it does not relate to a power generating method but it is necessary to suppress the power consumption all over the earth.

The energy supply from space may bring about the apprehension that it could break the thermal balance on the earth by transmitting energy which could never have been supplied to the earth by nature. Nevertheless, burning fossil fuels which accumulated on the earth since time immemorial is considered far more problematical for the thermal balance on the earth because the energy accumulated for years is consumed in a short time, thereby producing a significant quantity of heat. In microwave power transmission, the energy which could not naturally reach the earth would be certainly consumed here. Nevertheless, the microwave power transmission may well be deemed less influential over the thermal balance on the earth in proportion to the lower heat loss. In either case, however, the thermal balance on the earth will be inevitably affected to a significant degree. In other words, in the case of fossil fuels, the energy collected on a time basis is consumed on the earth, while in the case of microwave power transmission, the energy collected on a space basis would be consumed on the earth. From now on, it is considered necessary to study power consumption that would not break the thermal balance on the earth, as well as to develop highly efficient power which does not radiate any heat at all.

2. Outline of Energy Transmission System

2.1 Prerequisites for Wireless Power Transmission from a Power Plant on the Moon

Television and radio broadcasts and normal radio communications are a very poorly efficient wireless power transmission. As gathered from this fact, wireless power transmission with radio waves applied is based on a very simple operational principle. In other words, power is merely sent and received on a wireless basis. In the case of broadcasting or communications, it is possible to transfer the information if even only one hundred-millionth of the transmitted radio wave energy can be received. For wireless power transmission, however, it would be meaningless unless nearly 100% of the energy transmitted were received. This power transmission efficiency requirement is the most important difference between wireless power transmission and broadcasting and/or communications.

The present report is to study a system of transmitting and receiving the electricity from a power plant on the moon to a power-incoming base on the earth. Described below are the prerequisites for the study reported herein.

(1) The power transmission system is to be entirely made of the resources available on the moon.

Constructing a power plant on the moon would be meaningless if the materials of which the power transmission system had to be made were transported from the earth. A space solar power satellite on a stationary orbit would require a lower haulage cost than that for carrying the materials from the earth to the moon. The materials required to construct a moon power plant are to be sought for on the moon and a construction factory is to be built on the moon. Only the equipment and materials necessary for the factory are to be transported from the earth. If all materials could be arranged on the moon, it would only be necessary to build the construction factory. Subsequently, it would be possible to extend and proliferate the power transmission system on the moon. In addition, operation and maintenance could be conducted without being supported from the earth.

(2) There is not to be a radio relay point on the stationary orbit.

The wireless power transmission from the moon, which has been studied so far, must be provided with a relay satellite on the stationary orbit, by transmitting the electricity to a single power-incoming base on the earth. The microwave/laser transmitted from the moon must be received by rectenna/solar cells once and be converted to the microwave/laser again for power transmission to the earth. With the laser applied, the space solar power satellite so far proposed is to be employed as the relay satellite, which is to be composed of a solar cell to receive the laser from the moon, and a microwave/laser power transmission system to transmit the electricity to the earth. The relay satellite differs from the space solar power satellite in that the solar cell does not track the sun but the moon, and that the solar cell size varies with the magnitude of laser beams. In the case of microwave power transmission, the solar cell alone is changed into the rectenna. Thus, the relay satellite is generally identical to the space solar power satellite with minor differences. In addition, it has the significant disadvantage that the power transmission efficiency will decline to a great degree because of the two conversions, from microwave/laser to DC and from DC to microwave/laser. As mentioned above, we may come to the conclusion that constructing a space solar power satellite is more economical than building a relay satellite.

A system which does not employ any relay satellite, on the other hand, involves the problem that the power-receiving base must move according to the rotation of the erath on its axis. It is necessary, therefore, to normally scan beams, thereby tracking the power-receiving base. Once the power-receiving base has moved to the opposite side which cannot be directly observed from the moon, moreover, it is impossible to transmit electricity. It will be necessary, therefore, to provide two or more power-receiving bases so that the electricity will be transmitted while switching the beams. While no relay satellite is required, there is another disadvantage that two or more power-receiving bases are required. Nevertheless, a power-receiving base is a facility located on the earth. Making two or more power-receiving bases is considered easier than launching one relay satellite. In the next stage of the moon power plant, moreover, it may be readily expected that a space solar power satellite will be constructed from the materials available on the moon. While the electricity is not being transmitted from the moon, moreover, a power-receiving base may be used to receive the electricity transmitted from the space solar power satellite. In addition, it may be deemed applicable to the inter-continental power transmission, too. Thus, the power-receiving base is considered effectively usable.

(3) Even a small-scale system must be capable of transmitting a certain quantity of electricity.

If the power transmission system cannot be put into practical use before being put in full scale, it will be difficult to make investments in constructing a power transmission antenna. If a small-scale system were practically usable as it is, it could be developed step by step so that it would be all the more feasible. In the initial stages, the system should take into consideration a beam test and other applications (e.g. a synthetic aperture radar for remote sensing). If extended further in size, moreover, the power transmission system could be used to transmit electricity on the moon. And another possible application is an ultra-large antenna for astronomical observations.

(4) The power transmission system is to have the same power transmission capacity of 5GW as that available with a space solar power satellite.

With consideration given to the future exhaustion of fossil fuels, environmental problems on the earth and economic issues, it is necessary that the energy supplied from the moon should be aimed at covering several tens of percent of the electric power consumed on the earth. Wireless power transmission, moreover, requires much cost for its construction. It is more applicable to a full-scale power transmission than to a small-scale one. The larger the size, the more economically the power will be transmitted. The study reported herein, however, has been the first trial, which accordingly involves many uncertainties. As a result, it is easier to think about the same power transmission size as that for the space solar power satellite which has been so far studied in many cases. The proposed power transmission system has been set to a power transmission size of 5GW, accordingly.

2.2 Technological Potential of Wireless Power Transmission

Discussed hereunder are the technological possibilities for wireless power transmission on the prerequisites discussed in 2.1 above.

(1) Studying the Frequency of the Transmitting Wave

The most crucial item for wireless power transmission is the frequency of the electromagnetic wave used for power transmission. An electromagnetic wave has a frequency range widely extended from a low frequency to an optical level. Since beams must be sent from the moon to the earth, however, the applicable frequency band is limited to a microwave thru a laser beam. Table 2.2-1 summarizes a comparison of the power transmission systems with microwave, millimeter wave and laser, respectively, applied. CWC in the table, meanwhile, is an abbreviation of the Cyclotron Wave Converter developed in the University of Moscow. A study of frequencies is shown below.

1) The higher the frequency, the more easily beams can be made to converge. One feature of a high frequency (specially laser) is that the related power-transmitting/receiving system will be small-sized.

2) The more concentrated the beams, the higher the energy density will be and the more dangerous it will be. A high-power laser beam will turn out to be an arm, such as SDI, which is very hazardous against anything that crosses the beam.

3) The study reported herein is not to employ a relay satellite on the stationary orbit. The power transmission system on the moon, therefore, must take into consideration an attenuation due to the atmosphere and rainfalls on the earth. Fig. 2.2-1 shows the rainfall attenuations by frequency. A rainfall attenuation becomes significant at 10GHz and above. A frequency of 2.4GHz, which is envisaged for a space solar power satellite, may well be deemed completely free from attenuation due to the atmosphere.

   In the case of a laser beam, we should be aware of the hazard of the beams scattered by the atmosphere. Their effect on living things, in particular on the eyes, should be examined fully.

4) According to the prerequisites for the use of resources available on the moon, not GaAs but Si is to be applied to a microwave amplifier. An Si transistor compares unfavorably with GaAs in terms of efficiency. And the technology currently available has an Si transistor limited to a frequency of 2.45GHz at the most. A frequency higher than that would make the Si transistor very poorly inefficient. Nevertheless, no haulage cost will

be incurred with amplifiers produced on the moon. As long as cooling is performed satisfactorily, the poor performance may be offset by the number of amplifiers.

From the study results mentioned above, a 2.45GHz power transmission system with Si transistors applied has been selected for the study reported herein. It should be added that a low frequency other than the ISM band (2.45GHz) may be approved for power transmission in practical use.

(2) Studying an Energy Beam

Fig. 2.2-2 shows the radiation pattern of an ideal power transmission antenna and the ratio of the power reaching the power-receiving antenna to the transmitted power (efficiency). The aperture surface shows a Gaussian distribution of 1/10 at the end of the antenna. In this distribution, the main beam is thick while the side lobe is small. Its power transmission efficiency reaches 95% or more at 2 on the axis of abscissas. The value on the axis of abscissas, meanwhile, is dependent upon the power-outgoing and -incoming antennas' Areas A_t and A_r, the Wave Length λ and the Power-transmitting Distance D. If the wavelength is reckoned as 12 cm (2.45GHz) and the power-transmitting distance as 1km, for example, it will be possible to transmit power at an efficiency of 95% or more by using the power-outgoing/incoming antennas with a radius of 8.8 meters.

If such conditions as a microwave power distribution on the ground, etc. are set completely identically to those for the space solar power satellite, it is possible to directly apply the results of studies made by the DOE and NASA. In other words, the calculations referred to above allow us to gather that the rectenna has a size of 10 kilometers in diameter, which is identical with that of the SPS reference system, provided, however, that the power-transmitting antenna is given a diameter of 9 kilometers. Then, the power can be received with identical efficiency while the microwave power is distributed identically in the incoming power base. The maximum power density of microwaves, moreover, can be suppressed to $230W/m^2$ to remove their effects on the ionosphere. Based on the considerations referred to above, the power-transmitting antenna and the rectenna have been set to diameters of 9 and 10 kilometers, respectively. To increase the power to be transmitted in the future, it is necessary to make a satisfactory study of the effects on the ionosphere and of the influence on the environment, such as the impact on living things. For the purpose of testing the interaction between large-power microwaves and ionospheric plasmas, the MINIX rocket experiment was conducted in 1983. Fig. 2.2-3 shows the HF-band wave motion spectrum observed in that experiment. A difference of microwaves between ON and OFF was observed by exciting a frequency of 1.5 times the cyclotron frequency and a plasmatic wave in the plasma frequency band. Aiming at a more detailed quantitative experiment, moreover, the ISY-METS rocket test was conducted in 1993, using an active phased array antenna capable of freely controlling beams. As a result, it was confirmed that a power flux density of 230W/m^2 defined in the reference system would not excite any plasma wave motion. The conclusion has been made that the wave motion observed in the MINIX rocket test was excited by a very strong microwave at 150kW/m^2 around the plane of a horn antenna aperture.

(3) Studying a Rectenna Site

To transmit the power from the moon directly to the earth, a number of rectennas are required. The larger the number of rectennas, the more frequently microwave beams will have to be selected and the shorter the power-incoming time covered by one rectenna. A microwave can be incident upon the rectenna at an angle nearly vertical to the rectenna plane. As a result, the rectenna will be shaped nearly like a circle. If there is a small number of rectennas, on the other hand, each of them will have to cover a wider range of elevation angles, being shaped into an ellipse. If rectennas are located near the equator as shown in Fig. 2.2-4, it is possible that rectennas may be installed at four locations. Even if they should be located on the sea completely off the shore, it may be considered appropriate to install two on the Pacific Ocean and one each on the Indian Sea and on the Atlantic.

If rectennas are installed at four locations on the earth, an elevation angle range of 90 degrees from -45 to 45 degrees is to be covered by each rectenna. And each rectenna will have a size of 14 kilometers from east to west and of 10 kilometers from north to south. If it is assumed that a microwave beam can scan from north to south, it will be possible to transmit the power anywhere on the earth, without being limited to an area on the equator. However, the moon will have a lower elevation angle according to the latitude. As a result, the rectenna will have to be longer from north to south.

2.3 Basic Concept of Power Transmitting and Receiving System

Based on the studies reported above, we will propose a basic concept of an actual power transmitting and receiving system.

(1) Power-transmitting Antenna

For power-transmitting antenna, an active phased array antenna with a diameter of 9 kilometers is to be employed as discussed in 2.2 (2). As shown in Fig. 2.3-1, the antenna is made floating above the surface of the moon to form a plane, whose accuracy is set to a standard accuracy of within about 1 centimeter (λ /10). Nevertheless, it is possible to correct an error from the plane by controlling the transmission phase.

The power-transmitting antenna is composed of many sub-arrays. The transmission phase is controlled on a sub-array by sub-array basis while the power-transmitting antenna is entirely functioning as a phased array one. The sub-array is sectionalized into a hexagon near the circle as shown in Fig. 2.3.1. The sub-arrays need not be fabricated as structurally classified. All the antennas within the sub-arrays, however, should be controlled in an identical phase. They should be desirably constructed into the monoblock which scarcely distorts.

(2) Sub-array

The sub-array comprises a collection of antenna elements (e.g. a dipole antenna plus an amplifier), each of which is the ultimate base unit. On the principle of a phased array antenna, a smaller-sized sub-array will have its radiator pattern (half-value width) extended so that microwave beams can scan a wider range. In addition, grating lobes will have intervals also extended at a lower level. In an optimum system, a grating lobe will not appear if the phase is controlled on a half wave-length by half wave-length basis. Controlling the phase with all antenna elements, however, would enlarge the system excessively. The conditions under which a sub-array size is determined, therefore, may be set to 1) and 2) below.

1) Beams can scan the entire earth.

The rectenna moves, coupled with the rotation of the earth on its axis. To track the rectenna, beams must be able to scan an angular range of 2 degrees (earth diameter 12,800km/earth-moon distance 360 thousand kilometers). It will be studied in comparison with the half-value width of a sub-array. An antenna which has a half-value width of 2 degrees will have a diameter calculated to be 3.4 meters. From this calculation, it may be gathered that the sub-array must have a size of 3.4 meters or less. The transmitting power, moreover, will decrease if beams are swung in a large sub-array. Preferably, therefore, the sub-array should be as small as possible.

2) A grating lobe must not affect anything other than the power-receiving base.

In the space solar power satellite reference system, a grating lobe appears every 400 kilometers with the sub-array having a size of 10 meters.

From the study made as indicated in 1) above, however, it may be calculated that the grating lobe nearest the main beam will appear in the direction of 11,800 kilometers from the center of the earth if the power-transmitting antenna on the surface of the moon has a sub-array diameter of 3.4 meters. This calculation result is such that the grating lobe is directed at 1 degree opposite when beams are scanned once. In the case of four rectenna sites, the system will scan 0.7 degrees only so that no grating lobe will be directed toward the earth. If the sub-array is sectionalized into small ones in this case, the grating lobes will get away far from the earth, thereby securing safety.

(3) Beam Control Method

A retrodirective antenna system has been proposed as the beam control system for wireless power transmission. The retrodirective antenna system is to transmit a pilot signal from a rectenna site as shown in Fig. 2.3-2. On the transmitting side, the pilot signal is received to create a conjugate phase of pilot signals. If a microwave is transmitted from the power-transmitting antenna in this phase, beams will converge at the rectenna site which has transmitted the pilot signal. Briefly, it signifies that the distance of the rectenna site (with the antenna transmitting a pilot signal) from each rectenna is calculated by receiving the pilot signal. Even if the rectenna is relocated, the related fluctuation may be corrected, based on the pilot signal phase.

The retroactive antenna system will be simplest when the pilot signal has the same frequency as that of the power-transmitting microwave. In principle, the power can be transmitted accurately to the rectenna site. As long as the pilot signal has the same frequency as that of a power-transmitting microwave, the pilot signal receiver on the power-transmitting antenna side will fail to discriminate the pilot signal from the microwave which the power-transmitting antenna itself is transmitting. Besides, if the pilot signal frequency is shifted slightly, the microwave beam direction will deviate from the rectenna site in a stroke equivalent to that shift. The reference system proposes a method of detecting a phase difference of the power-transmitting microwave frequency which is synthesized on the receiving side by the use of the pilot signals at two symmetrical frequencies ($f + \Delta f$ and $f - \Delta f$) (as illustrated at the top in Fig. 2.3-3). This system, however, has a significant defect. To detect the phase difference at the power-transmitting microwave frequency, first of all, it is necessary to convert to twice the frequency by calculating $(f + \Delta f) + (f - \Delta f)$ and to obtain f by calculating f/2. A calculation of f/2, however, has two solutions, one of which is to deny the beams deviated by π. Thus, control will be unstable. We have proposed an asymmetrical two-tone ($f + \Delta f$ and $f + 2\Delta f$) system (as illustrated in the middle of Fig. 2.3-3), which has been empirically proven to operate normally. Results involved are shown in Fig. 2.3-4. In the asymmetrical two-tone system, $f + \Delta f$ may be successively multiplied to obtain a difference from $f + 2\Delta f$ only. Thus, the phase difference at f can be obtained without dividing. Nevertheless, the circuit is complicated, involving a large number of parts. Next, we will propose a method of using a frequency equivalent to half the power-transmitting microwave as the pilot signal (as illustrated on the bottom in Fig. 2.3.3). In this case, a mere successive multiplication would permit processing to be carried out so that a very simple circuit system can be established. The propagation characteristic in the ionosphere, however, may differ. And it is considered necessary to confirm this effect of the ionosphere in reality.

The retrodirective antenna system is a technology essential where a power-transmitting antenna must be flexibly constructed to reduce the weight as in case of the space solar power satellite. If the antenna normally has a constant plane as fixed like on the surface of the moon, however, it is possible that the functions of a retrodirective antenna system may not be required. Another beam control method is to control the phase shift together with sub-arrays. A pilot-signal applied interference method or an optical survey may be used to accurately determine the direction of a rectenna site so that the microwave beams are controlled by being directed toward the rectenna site. It is also possible to correct the beam control by obtaining a distribution of those microwave beams which have arrived at the rectenna site. This control method is to arithmetically obtain the value of each phase in a computer, thereby leading to a system of high flexibility from a software point of view. The rectrodirective antenna system, moreover, requires a pilot receiver on a sub-array by sub-array basis. In other control methods, however, the system will only materialize with a simple phase shifter composed of a diode.

The beam control is the key technology in transmitting power in a microwave. To study the beam control system optimum on the surface of the moon, it is considered indispensable to conduct experiments, with a simple retrodirective antenna system and an interference meter installed on the moon surface.

(4) Antenna Elements and Amplifier

Antenna elements must be arranged without clearance all over the power-transmitting antenna. If an antenna element which has a wide effective aperture area (high gain) is employed, it will be possible to reduce the number of antenna elements required. Using a dipole antenna with low gain would increase the number of elements to a large degree. The dipole antenna, however, is composed of a rod material only so that it can be fabricated with ease. A dipole antenna, in particular, has a wide bandwidth, and is characterized by the significant advantage that its sensitivity will not vary even if the antenna, etc. should expand or shrink due to temperature differences between daytime and nighttime. In the study reported herein, therefore, the dipole antenna has been selected from the viewpoint of ease with which it can be manufactured on the moon.

As discussed in the prerequisites, the amplifier is to employ an Si transistor. And an F-class amplifier which has the highest efficiency for an amplifier configuration will be employed. As shown in the circuit diagram of Fig. 2.3-5, the F-class amplifier is to achieve an infinite impedance for odd harmonics by the use of a $\lambda/4$ line and a tank circuit while making a collector voltage square by the use of a filter so as to zero the impedance for even harmonics. In other words, as long as an electric current is flowing through the transistor, the amplifier will have the collector voltage zeroed to minimize the transistor power consumption, thereby increasing the efficiency. From this principle, the F-class amplifier does not only increase the efficiency but also naturally effectively removes the higher harmonics which interfere with communications, etc.

A semiconductor amplifier has a low gain (up to 10 dB), differing from an electron tube. A cascade connection, therefore, allows for the formation of a large-power amplifier. To employ an amplifier with an output of 10W, for example, the power is amplified from the reference oscillator to 10W, which is in turn divided by 10. The power divided into ten is further output at 100W with ten amplifiers. This cascade amplification permits a transmitting power of 7GW to be obtained at the amplifier in the final stage. If this system requires a group of 109 amplifiers in the final stage, it is necessary to provide a group of 108 or more amplifiers in the preceding stage. As a result, the system is of complex construction while each amplifier also requires complicated adjustment. If an amplifier in the initial stage should fail, furthermore, the entire system will stop, probably causing a serious problem. We therefore propose that an active antenna should be applied. This is an oscillator combination antenna, which has an oscillator in each element. Oscillators are interconnected so that their frequency and phase are controlled. If an active array antenna system can be composed of active antennas, we may expect that the number of amplifiers can be reduced while improving their reliability.

Concerning the oscillating frequency and transmitting phase of an active antenna, however, there are a lot of research challenges to be tackled.

To compose an antenna element of active antennas, no printed circuit board is employed but both antenna and oscillator (F-class amplification) should be constructed as one. This construction allows all passive elements, such as capacitor, etc. to be configured in a three-dimensional circuit while the Si-transistor only serves as a circuit element. This will reduce the number of parts required and will make an antenna element modular so that it can be replaced very easily.

The Si transistor is very highly reliable and it may be deemed scarcely necessary to replace a failed antenna element. Nevertheless, it goes without saying that a trouble shooting system is also required. As shown in Fig. 2.3-6, an output may be readily monitored if a distributor and a diode-applied simple rectifier circuit are added. With these connected, it is possible to measure the output level of the entire system. If an LED is connected, a simplified output level is also readable on an antenna element by antenna element basis.

(5) Power-receiving System

A communication antenna collects the radio waves which have arrived, out of which it takes a signal. To this end, a phase synthesis means and an amplifier are required. A power-receiving antenna for wireless power transmission, however, differs from the communication antenna in the sense that the microwave which has arrived at the power-receiving antenna is efficiently converted into electric power only. Thus, a phase synthesis or the like is not required while only the microwave need be rectified. In the reference system, a rectenna (RECtifying AnTENNA) has been proposed as a power-receiving element, which is a combination of the dipole antenna, invented by Bill Brown, with a diode. The rectenna element, which is independent of any other elements, has characteristics as a dipole antenna. On Plane H, therefore, the rectenna element is isotropic, thereby having the significant feature that the microwaves incoming in every direction can be received as power. When the power is transmitted directly from the moon, microwaves will be incident over a wide elevation angle range of 45 thru -45 degrees. The rectenna, therefore, may be deemed suitable as a power-receiving antenna. Another power-receiving antenna conceivable is a combination of the parabolic antenna with a microwave-DC converter (e.g. cyclotron wave converter: CWC). This power-receiving antenna, however, needs to track the moon to receive the power from it.

Table 2.2-1 A Comparison of Microwave/Millimeter Wave Power Transmission with Laser Power Transmission

	Mocrowave	Millimeter wave power transmission	Laser power transmission
System	Ultra-large	Large	Small (one-fiftieth of 100GHz)
Power-receiving	Rectenna/CWC (completely developed)	Rectenna/CWC (under development)	Solar cell (accomplished)
Efficiency	80%	60%	60%(GaAs) 40% (Si)
Beam control	Retrodirective antenna	Retrodirective antenna	Mechanical
Power flux density	Large power	Large power	Solar cell's temperature characteristic (Efficiency will decrease while the temperature rise.)
Oscillator Tube	FET	Gyrotorn Free Electron Laser	Free Electron Laser
Dangerousness	Protected with a shield	Protected with a shield	SDI
Machining accuracy	Rough	Precise	Mirror face
Problem	Ultra-large	Not developed, efficiency and oscillator tube	Beam control and oscillator tube

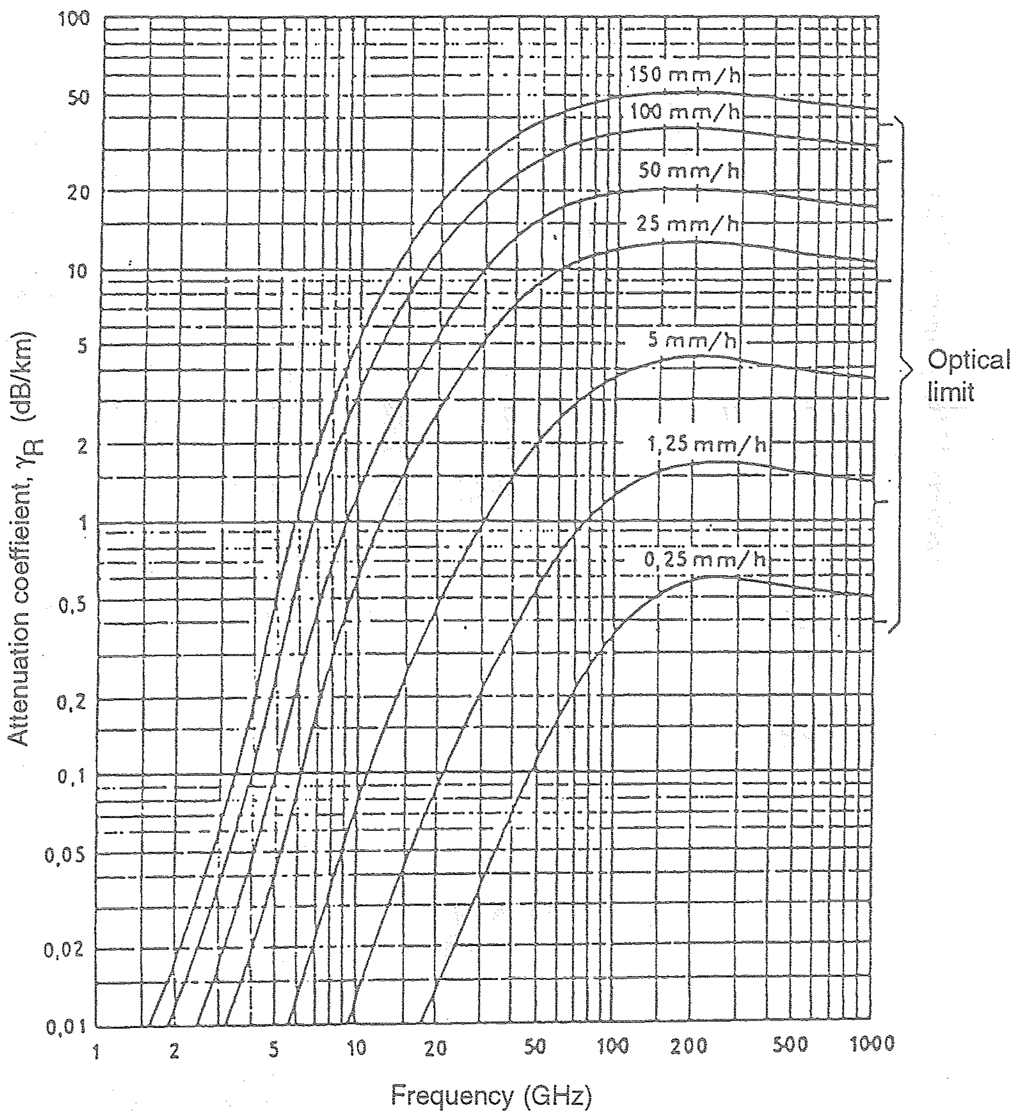


Fig. 2.2-1 Rainfall Attenuation

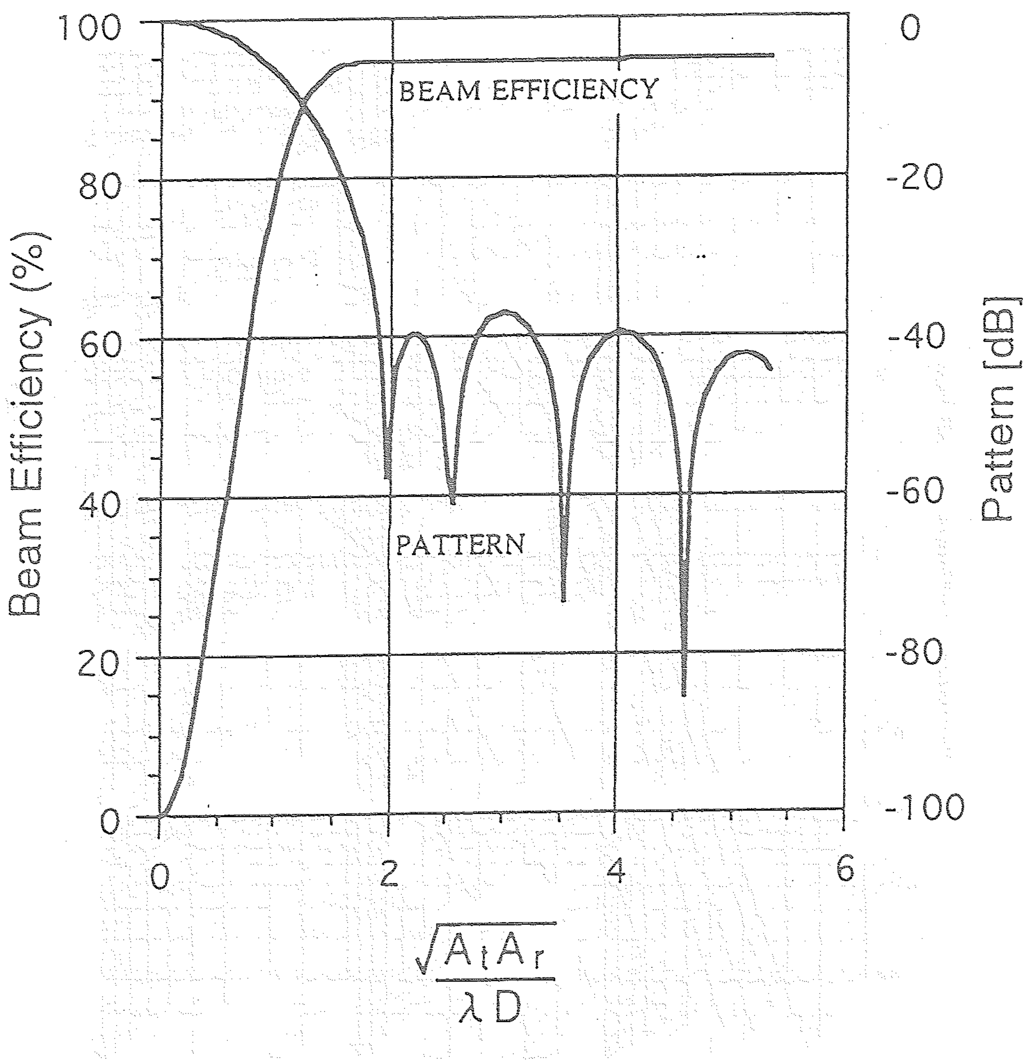


Fig. 2.2-2 Power Transmission Efficiency and Radiation Pattern

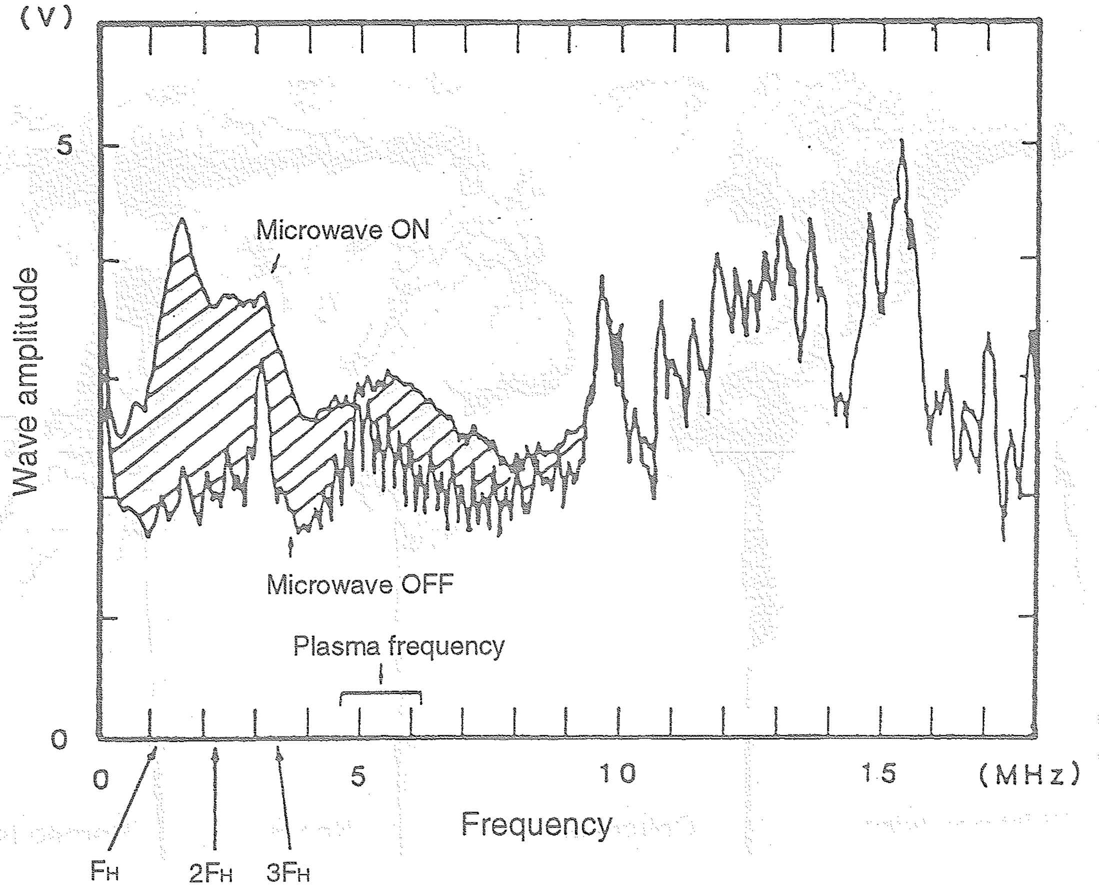


Fig. 2.2-3 Plasma Waves Observed in the MINIX Experiment

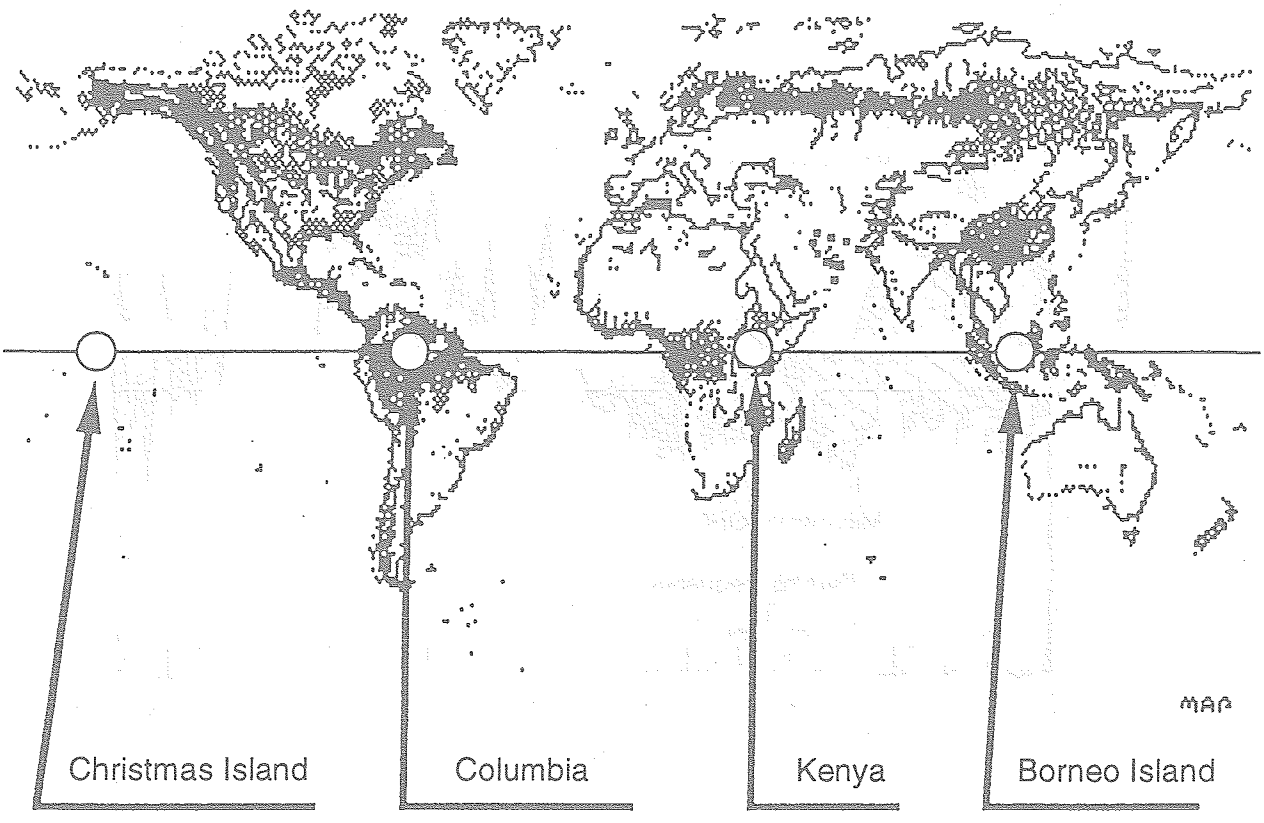


Fig. 2.2-4 Power-receiving Sites

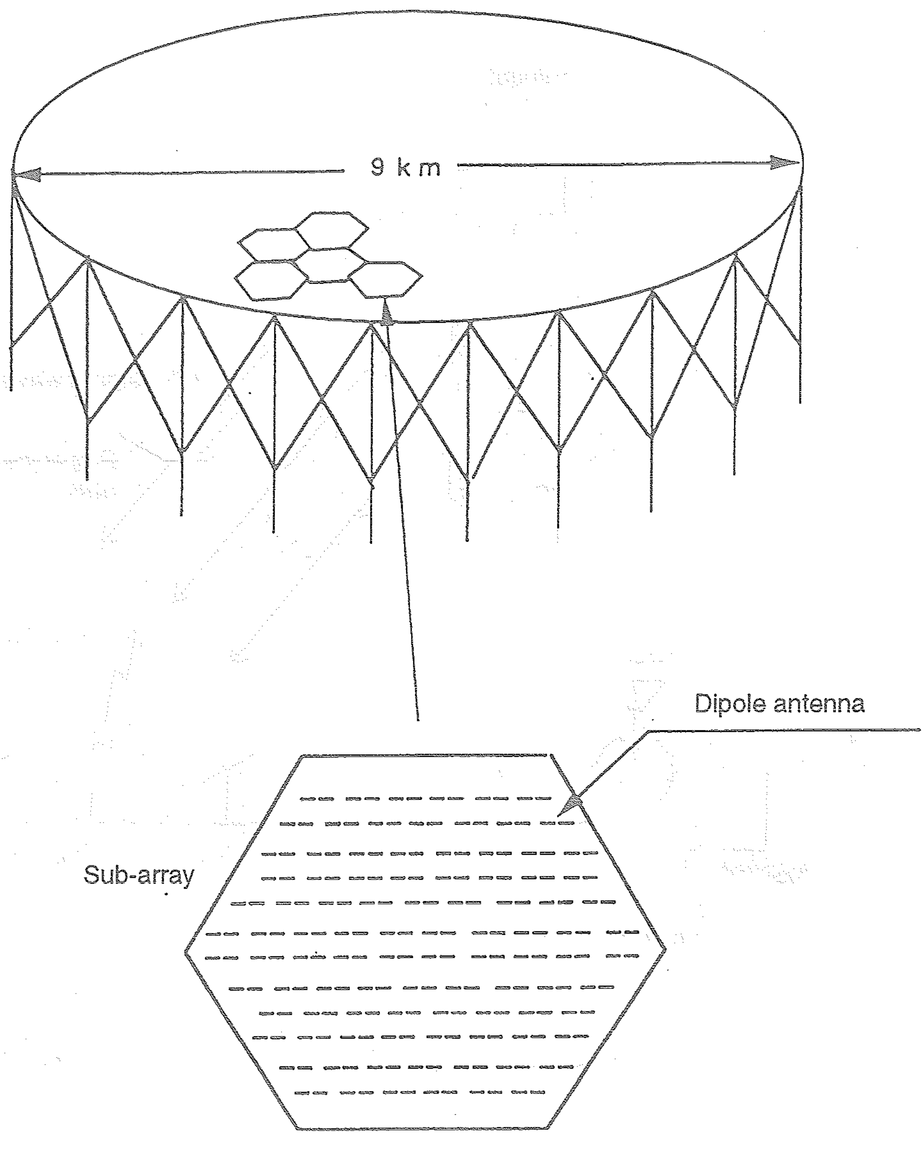


Fig. 2.3-1 An External View of Power-Transmitting Antenna

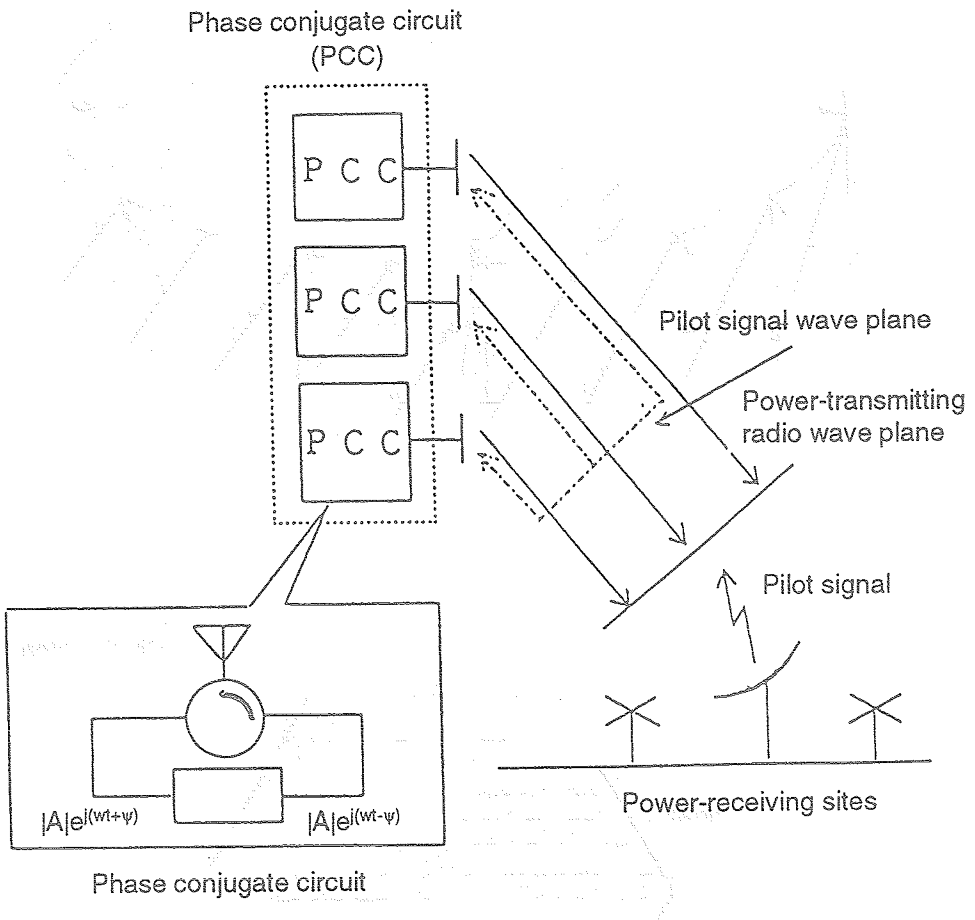
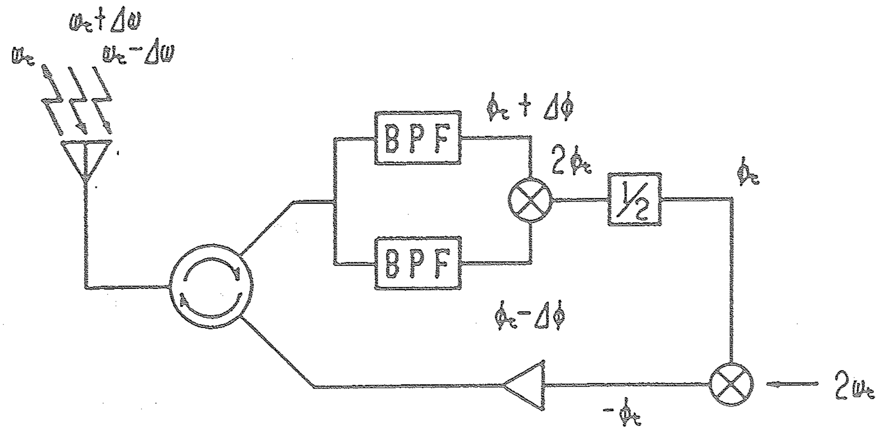
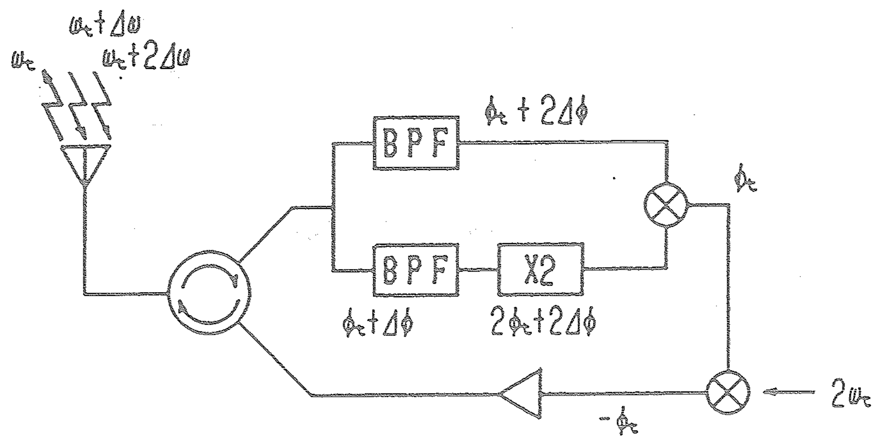


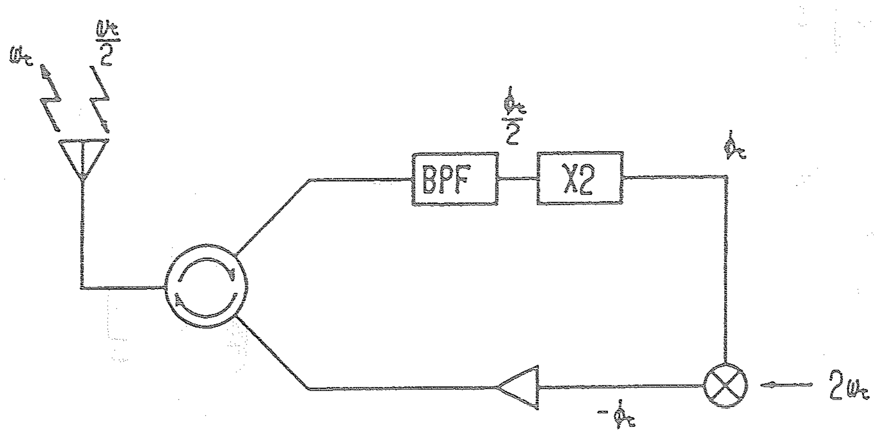
Fig. 2.3-2 Illustrative Principles of Retrodirective Antenna System



Symmetrical two-tone



Asymmetrical two-tone



Half frequency

Fig. 2.3-3 Pilot Signal Processing Circuits

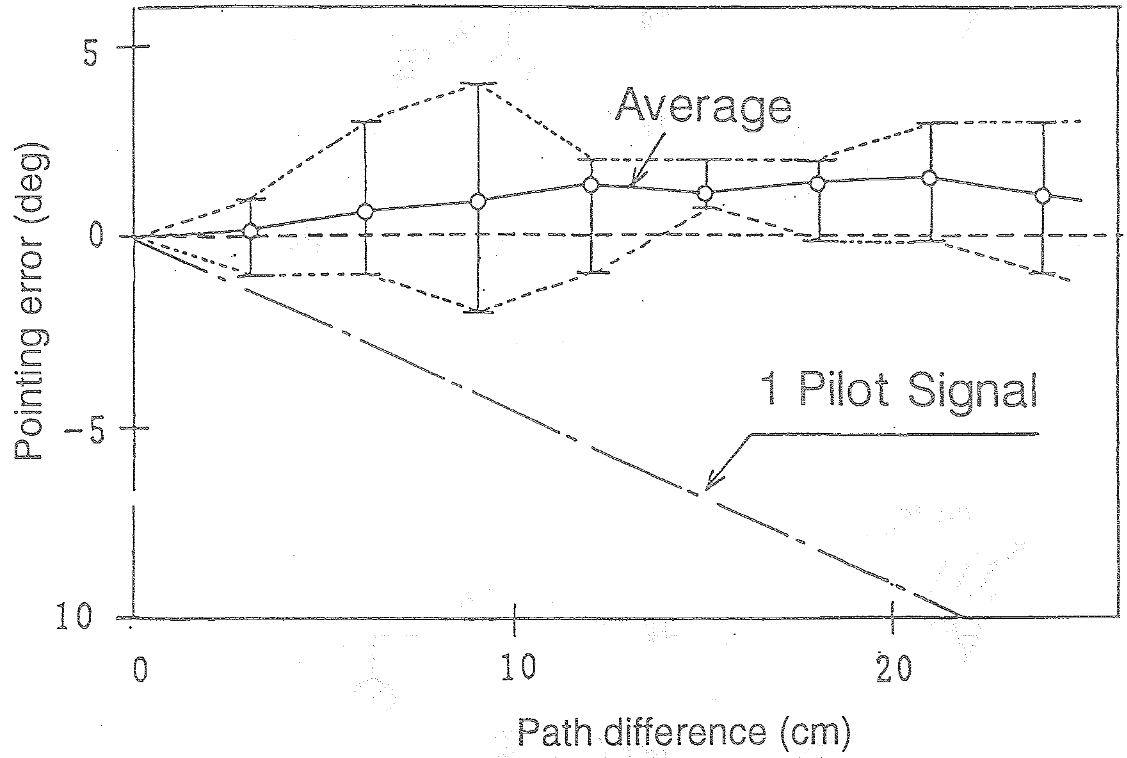


Fig. 2.3-4 Experimental Results with Asymmetrical Two-Tone System

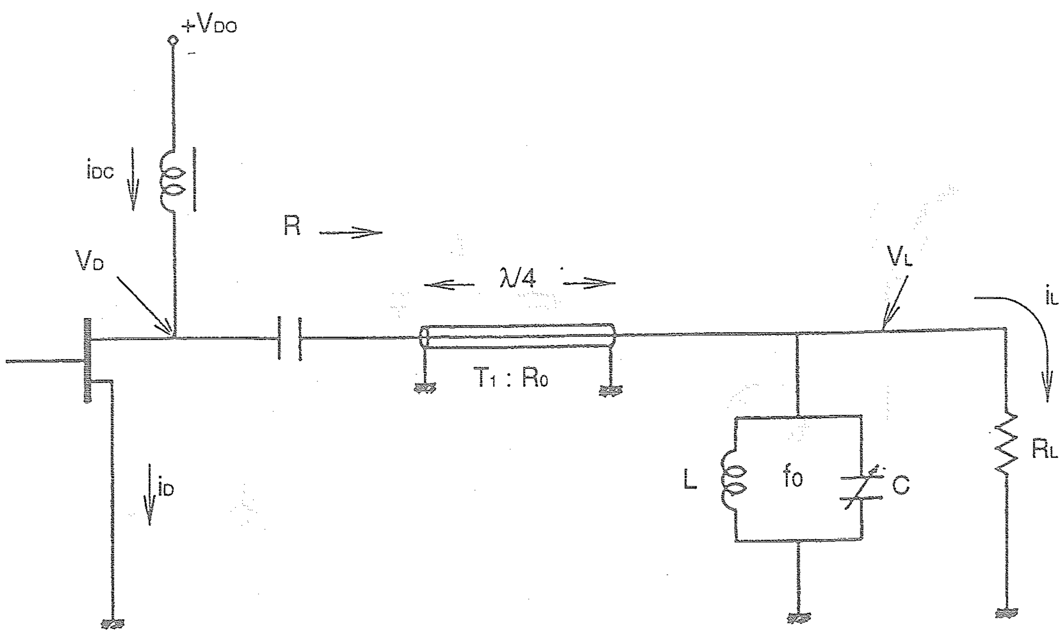


Fig. 2.3-5 Illustrative Principle of F-Class Amplifier

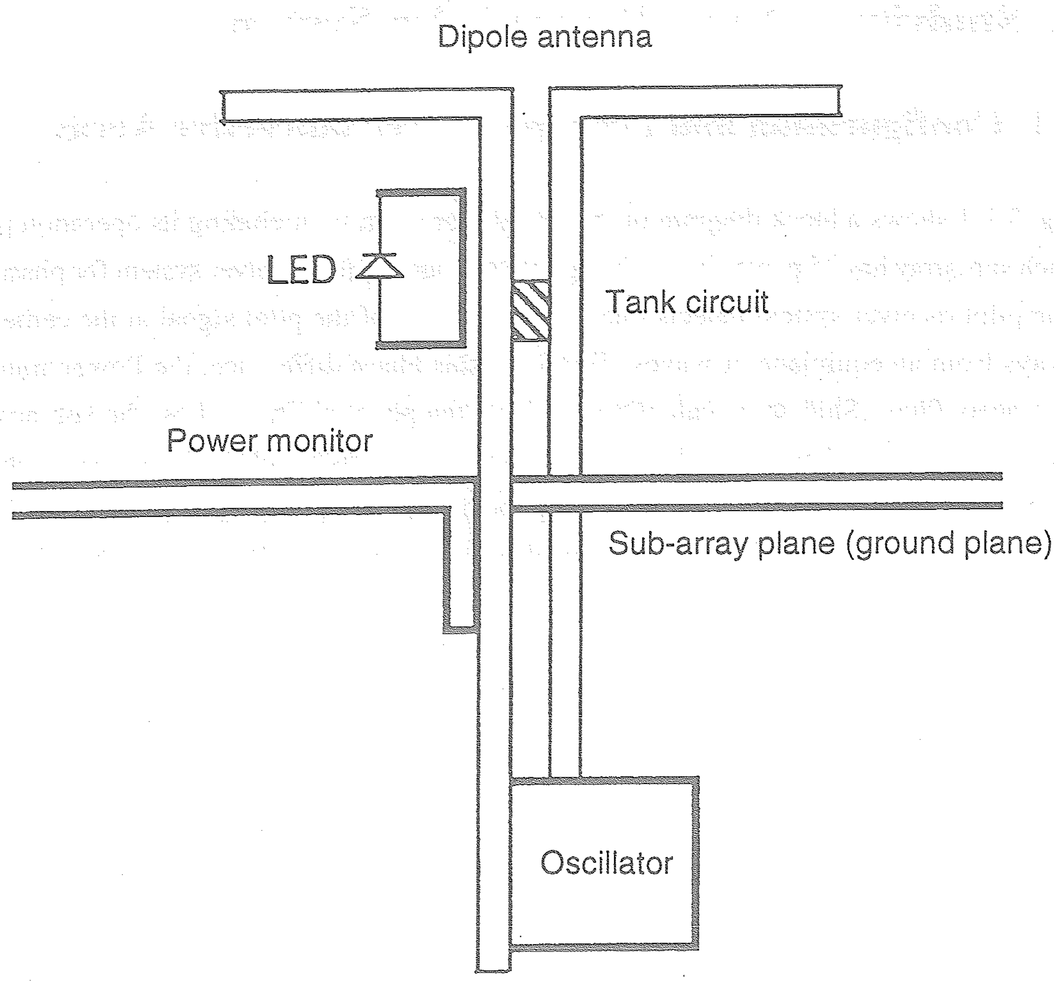


Fig. 2.3-6 Active Antenna Element

3. Studying a Power Transmission System

3.1 Configuration and Principle of Retrodirective Array

Fig. 3.1-1 shows a block diagram of the retrodirective array, including its operation principle. Each sub-array has 75 power-transmitting antennas and a pilot receiver system for phase control. The pilot receiver system detects Phase Difference Φ of the pilot signal at the center of sub-arrays from an equiplane of waves. Based on this phase difference, the Power-transmitting Sub-array Phase Shift Φ' is calculated to drive the phase shifter. Thus, the sub-arrays with their transmitting phase controlled to the received pilot signal phase have a synthetic output wave plane come in line with the received pilot signal wave plane. This permits the directivity of a power-transmitting signal to be controlled normally in the direction of the pilot.

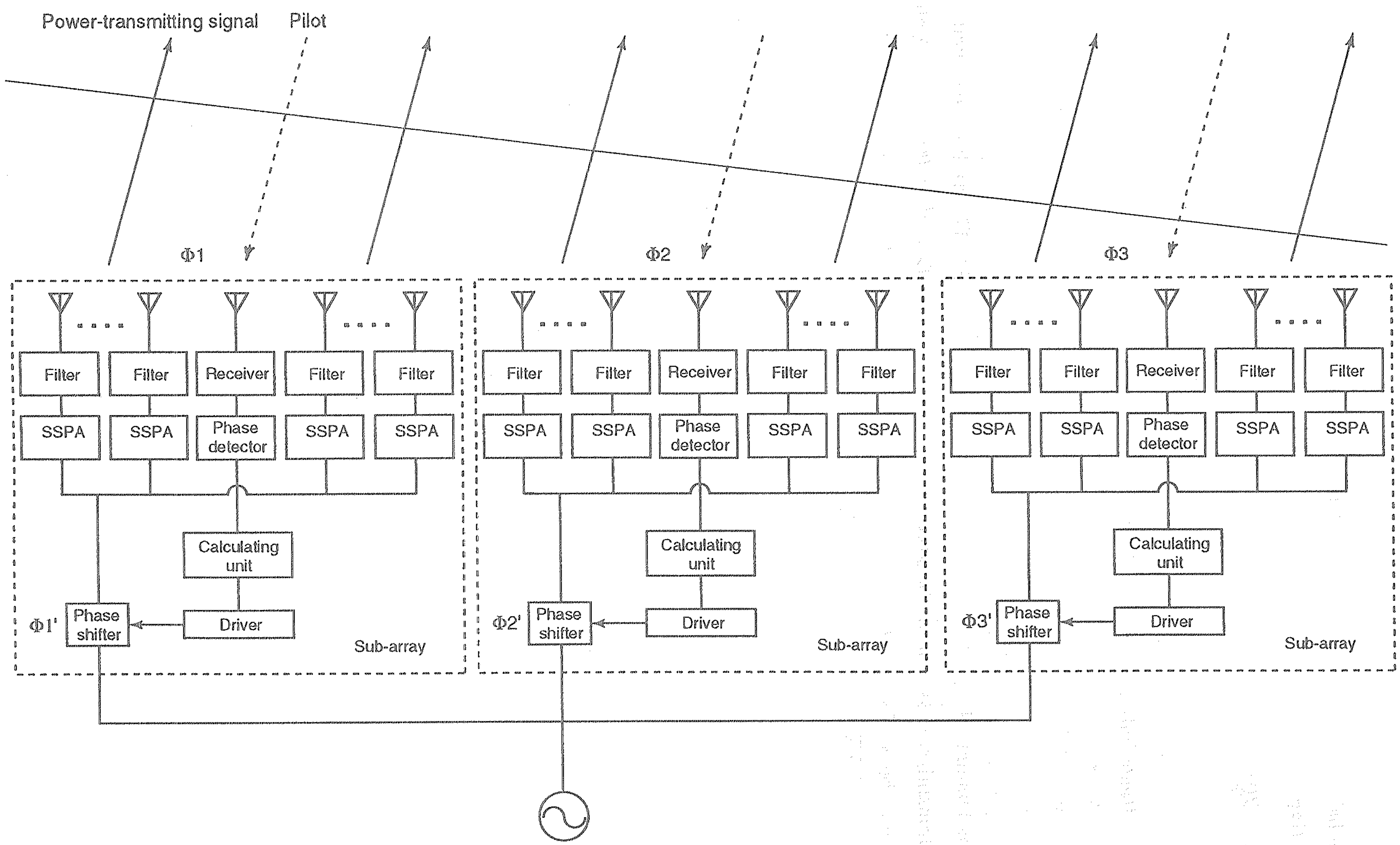


Fig. 3.1-1 Configuration and Operation Principle of Retrodirective Array

3.2 Beam Width

The beam half-value width (width in which half the power is included) of an antenna is generally given by Expression (1).

$$B = \frac{70\lambda}{D} \qquad (1)$$

where

B : Beam half-value width (degrees)
D : Antenna diameter (meters)
λ : Wavelength (meters)

If Antenna Diameter D = 10km and Frequency f = 2.45GHz (λ = 0.122m), both assumed for a power transmission system in the glass ocean on the moon surface, then Beam Half-Value Width B will be 8.57×10^{-4} (degrees). This beam width is equivalent to a spot diameter of approximately 5.8 kilometers on the earth.

3.3 Beam Steering

3.3.1 Requirements

The moon revolves both on its own axis and around the earth in an identical cycle. As a result, it normally has the same side directed toward the earth. Nevertheless, the moon has an elliptic orbit, with its equator plane inclined at 6.7 degrees to the orbital plane. The moon, therefore, performs a gooseneck motion, though slightly. This motion is called the balance action. And it causes an apparent moon surface center to deviate at a maximum of about 7 degrees relative to the mean moon surface center. The power-transmitting system in the glass ocean, therefore, should permit antenna beams to be driven within a range of the mean earth-oriented direction ±1 degree.

A deflection of beams would lead to a decrease in power-receiving efficiency while causing the power flux density to rise around the power-receiving antenna. These, therefore, need be taken into consideration in determining a beam steering step. The study reported herein has been made on the assumption that the center of beams is to be controlled within $1/10^5$ of the beam width. It is necessary, however, to study a detailed beam-orientation control requirement, with power-receiving efficiency. etc. separately taken into consideration.

3.3.2 Number of Bits in Phase Shifter

If a phase shifter has a small number of bits, the phase shift will have an increased quantification error, leading to a decrease in gain while causing beams to have an error in the beam-scanning direction. If the phase shifter has a large number of bits, on the other hand, beams can be smoothly scanned. Nevertheless, the phase shifter will have an increased insertion loss, leading to a decrease in antenna gain. It is necessary, therefore, to minimize the number of bits in the phase shifter as far as the beam scanning characteristic so permits.

If a phase shifter with i-bits is employed, the decrease in gain will have Minimum Possible Setting Phase Shift $B = 2\pi/2^i$ and Maximum Phase Shift Error of $\pm B/2$. If the quantified phase errors are uniformly distributed in a section $\pm B/2$, the scanning antenna will have Gain G on a mean basis as follows:

$$G = \frac{2(1-\cos B)}{B^2} G_0$$

where G_0 is an ideal gain which contains no quantified phase error.

In the power transmission system in the glass ocean, the quantification is considered to make an orientation error more problematical than a gain loss.

A beam-scanning direction error may be evaluated by the granularity which represents the extent to which beams can be scanned in detail. A straight array antenna with Number of Elements N may have a mean granularity expressed, being standardized in terms of Beam Width θ_{HP} as follows:

$$\frac{\Delta\theta}{\theta_{HP}} = \frac{1}{2^{i-1}N}$$

where a beam width of about 8.57×10^{-4} will apply in the case of a ø10km power-transmitting antenna in the glass ocean. In the expression above, the number of sub-arrays (5.5 million pieces) falls in the glass ocean power transmission system composed of sub-arrays.

If a 3-bit phase shifter, which can be configured with relative ease, is employed, the orientation error will remain at approximately $1/(2.6\times10^{6})$ of the beam width, which may be deemed satisfactory as orientation accuracy.

4. Studying a Feeder System

4.1 Profit and Loss in AC and DC Feeders

Table 4.1-1 shows the general profit and loss in AC and DC feeders. Including the previously reported study, the glass ocean is assumed to employ a DC feeder system.

Table 4.1-1 A Comparison of AC and DC Feeders

Item	AC feeder	DC feeder
Switch Station/AC-DC converter station	A switch station is less expensive than an AC-DC converter station.	An AC-DC converter is more expensive than a switch station.
Long-distance large power transmission	To transmit the power over a long distance, the charging current will become problematical. It is difficult to use cabling for long-distance large-power transmission.	Power can be transmitted over a long distance without a reactive power loss or a dielectric loss.
EMI	A countermeasure is required.	Readily controllable
Discharge	A countermeasure is required for corona discharge.	No countermeasure is required.
Harmonics generated	No harmonics are generated.	Harmonics are generated in the AC-DC converter.
Number of conductors	A large number of conductors is required, resulting in an expensive cable line.	A small number of conductors is required, resulting in an inexpensive cable line.
Reactive power	Loss due to the transformer is small.	A lot of reactive power is consumed at a converter station.
Voltage transformation	Easy (with a transformer)	Complicated (with a DC-DC converter)

4.2 DC Feeder Circuit

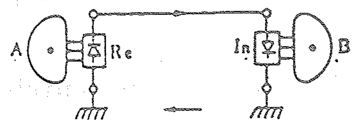
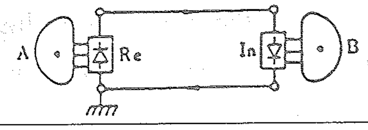
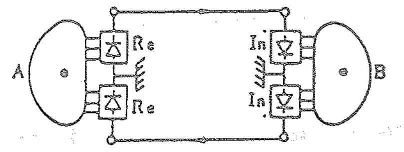
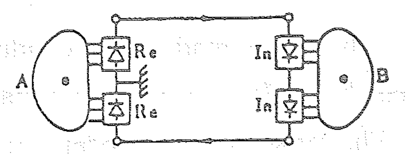
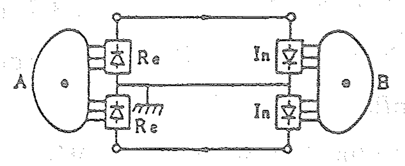
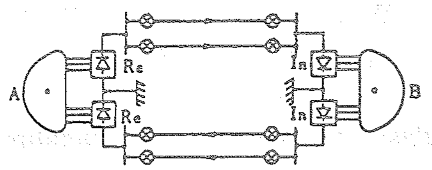
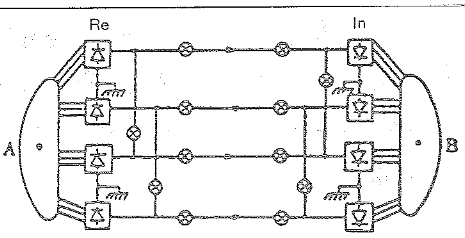
A DC feeder system may well have a feeder circuit configuration as shown in Fig. 4.2-1 (Reference 1). In a system on the earth, the power is considered to be transmitted between a power-transmitting terminal and a load. And it has a system configuration in which the power is finally fed in AC. In the glass ocean, the power is considered to be fed to a number of loads in a bus form. Nevertheless, there is a relatively short distance between loads, which may be considered as a concentrated load. And this way of thinking is directly applicable.

In a feeder system on the earth, a return to the ground and neutral point grounding are employed to reduce the number of lines. On the surface of the moon, such characteristics as ground resistance, etc. are unknown. It is considered impossible, therefore, to adopt a return to the ground.

The neutral-point grounding system which requires a balance between power generator and load, moreover, has a feeder circuit complicated. And grounding at the neutral point is also required. Therefore, the neutral-point grounding system is considered unsuitable for location on the surface of the moon. A multi-line transmission system is also considered unsuitable for use on the moon surface because of its complicated circuitry.

From what has been mentioned above, it may be considered reasonable to employ a conductor return system of monopolar single line transmission type for the feeder system in the glass ocean.

Reference 1: "Establishing a DC Power Transmission Technology," Society of Electricians (Corona-sha), 1978

System		Conceptual diagram
DC monopolar single line power transmission	Ground(sea water) return system	(1) 
	Conductor return system	(2) 
DC bipolar single line power transmission	Neutral-point double-end grounding system	(3) 
	Neutral-point single-end grounding system	(4) 
	Neutral line system	(5) 
Multi-line power transmission system (*)	(a) DC multi-line power transmission system	 (An example of two-line system)
	(b) Converter in-parallel DC multi-line power transmission system	 (An example of dual-line system, with 2 converters in parallel)

(legend) ⊙ Power supply and load line ⊗ High-speed switch or circuit breaker

Forward converter (Re) and reverse converter (In)

(*) Even a multi-line system is also available either monopolarly or bipolarly and in a variety of grounding methods, like the single-line system.
Shown here is the typical case of bipolar grounding at both ends.

Fig. 4.2-1 DC Two-Terminal Transmission System

4.3 Studying a Feeder Loss

4.3.1 Characteristics of Copper and Aluminum Wires

Tables 4.3-1 and 4.3-2, respectively, show the characteristics of copper and aluminum wires (Reference 2). Copper and aluminum have a difference of 1.5 times in conductivity. The aluminum wire, therefore, shows higher electric resistance. With the utilization of resources available on the moon, however, it will be necessary to use aluminum wires. Basically, giving the aluminum wire a larger conductor diameter will permit the loss to be reduced to a loss similar to that of copper wire.

4.3.2 Studying a Conductor Loss

Now, a study will be made of the conductor loss due to a feeder line. Since it is a loss due to resistance, the feeder loss is proportional to the feeder resistance and to a square of the electric current. The resistance of a feeder may be obtained by multiplying its distance by resistance per unit length. Figs. 4.3-1 and 4.3-2, respectively, show the losses of aluminum and copper wires where the feeder diameter is set to 12 mm, the same as the maximum diameter of a single mild copper wire. If the feeder line has a maximum one-way length of 10 kilometers, the aluminum wire will lose 2.5 Watts at a current of 1 ampere, 250 Watts at 10 amperes and 250 kilo-Watts at 100 amperes. With the feeder circuit in the conductor return inclusive, therefore, twice the loss will arise.

If the glass ocean has a power generating capacity of 100 kilo-Watts, the feeder line will have an allowable loss of 1 kilo-Watt both ways where it is allowed to lose 1%. Fig. 4.3-3 shows the results of calculating the loss at each current where the power is transmitted over 20 kilometers using a ø12mm aluminum wire. From Fig. 4.3-3, it may be gathered that 1 kilo-Watt is lost at a current of 14 amperes where the ø12mm aluminum feeder line is 20 kilometers long both ways.

From the above, we have set the feeder to a current of 14 amperes. Both feeder loss and feeder line section are parameters selectable over a wide range. These, therefore, are to be reviewed in the future when other restrictive conditions may arise.

4.3.3 Studying a Feeder Line

An electric cable on the earth is, in general, often a conductor covered with an insulator. This insulator coating is usually made of paper or of such a resin as polyethylene, vinyl, Teflon, etc.

With consideration given to the production of a feeder on the surface of the moon, it is considered difficult to obtain such insulating materials. And it is reasonable to use bare cables without insulator coating as the feeder lines in the glass ocean. An electric car is fed with power at a voltage of 700 thru 1,500 volts dc. Besides, the overhead feeder line is a bare cable. No technological problem, therefore, is involved in feeding power with a bare cable.

Table 4.3-1 Characteristics of Mild Copper Wire for Electricity (JIS C3102)

Diameter (mm)	Diameter tolerances (mm)	Sectional area (Reference) (mm^2)	Weight (Reference) (kg/km)	Conductivity 20°C (%)	Electric resistance (Reference) 20°C (Ω/km)	Tensile load (Reference) (kg)	Tensile strength (kg/mm^2)	Elongation 250 mm (%)
0.10	0.008	0.007854	0.06982	98.0 or more	2,240.0	-	-	15.0 or more
0.12	0.008	0.01131	0.1005	98.0 or more	1,556.0	-	-	15.0 or more
0.14	0.008	0.01539	0.1368	98.0 or more	1,143.0	-	-	15.0 or more
0.16	0.008	0.02011	0.1788	98.0 or more	874.9	-	-	15.0 or more
0.18	0.008	0.02545	0.2263	98.0 or more	691.3	-	-	15.0 or more
0.20	0.008	0.03142	0.2793	98.0 or more	559.9	-	-	15.0 or more
0.23	0.008	0.04155	0.3694	98.0 or more	423.4	-	-	15.0 or more
0.26	0.01	0.05309	0.4720	98.0 or more	331.4	-	-	15.0 or more
0.29	0.01	0.06605	0.5872	98.0 or more	266.4	-	-	20.0 or more
0.32	0.01	0.08042	0.7149	99.3 or more	215.9	-	-	20.0 or more
0.35	0.01	0.09621	0.8553	99.3 or more	180.5	-	-	20.0 or more
0.40	0.01	0.1257	1.117	99.3 or more	138.1	-	-	20.0 or more
0.45	0.01	0.1590	1.414	99.3 or more	109.2	-	-	20.0 or more
0.50	0.01	0.1964	1.746	100.0 or more	87.79	5.50 or less	28.0 or less	20.0 or more
0.55	0.02	0.2376	2.112	100.0 or more	72.56	6.65 or less	28.0 or less	20.0 or more
0.60	0.02	0.2827	2.513	100.0 or more	60.99	7.92 or less	28.0 or less	20.0 or more
0.65	0.02	0.3318	2.950	100.0 or more	51.96	9.29 or less	28.0 or less	20.0 or more
0.70	0.02	0.3848	3.421	100.0 or more	44.81	10.8 or less	28.0 or less	20.0 or more
0.80	0.02	0.5027	4.469	100.0 or more	34.30	14.1 or less	28.0 or less	25.0 or more
0.90	0.02	0.6362	5.656	100.0 or more	27.10	17.8 or less	28.0 or less	25.0 or more
1.0	0.03	0.7854	6.982	100.0 or more	21.95	22.0 or less	28.0 or less	25.0 or more
1.2	0.03	1.131	10.05	100.0 or more	15.24	31.7 or less	28.0 or less	25.0 or more
1.4	0.03	1.539	13.68	100.0 or more	11.20	41.6 or less	27.0 or less	25.0 or more
1.6	0.03	2.011	17.88	100.0 or more	8.573	54.3 or less	27.0 or less	25.0 or more
1.8	0.03	2.545	22.63	100.0 or more	6.774	68.7 or less	27.0 or less	25.0 or more
2.0	0.03	3.142	27.93	100.0 or more	5.487	84.8 or less	27.0 or less	30.0 or more
2.3	0.03	4.155	36.94	100.0 or more	4.149	112 or less	27.0 or less	30.0 or more
2.6	0.03	5.309	47.20	100.0 or more	3.248	143 or less	27.0 or less	30.0 or more
2.9	0.03	6.605	58.72	100.0 or more	2.610	172 or less	26.0 or less	30.0 or more
3.2	0.04	8.042	71.49	100.0 or more	2.144	209 or less	26.0 or less	30.0 or more
3.5	0.04	9.621	85.53	100.0 or more	1.792	250 or less	26.0 or less	30.0 or more
4.0	0.04	12.57	111.7	100.0 or more	1.372	327 or less	26.0 or less	30.0 or more
4.5	0.04	15.90	141.4	100.0 or more	1.084	413 or less	26.0 or less	30.0 or more
5.0	0.04	19.64	174.6	100.0 or more	0.8779	511 or less	26.0 or less	30.0 or more
5.5	0.04	23.76	211.2	100.0 or more	0.7256	618 or less	26.0 or less	30.0 or more
6.0	0.06	28.27	251.3	100.0 or more	0.6099	735 or less	26.0 or less	30.0 or more
6.5	0.06	33.18	295.0	100.0 or more	0.5196	863 or less	26.0 or less	30.0 or more
7.0	0.06	38.48	342.1	100.0 or more	0.4481	1,000 or less	26.0 or less	30.0 or more
8.0	0.06	50.27	446.9	100.0 or more	0.3430	1,260 or less	25.0 or less	35.0 or more
9.0	0.06	63.62	565.6	100.0 or more	0.2710	1,590 or less	25.0 or less	35.0 or more
10.0	0.06	78.54	698.2	100.0 or more	0.2195	1,960 or less	25.0 or less	35.0 or more
12.0	0.06	113.1	1,005	100.0 or more	0.1524	2,830 or less	25.0 or less	35.0 or more

(Note)

1. The sectional area, electric resistance, tensile load and weight specified in the table above are given in relation to the standard diameter.
2. Density of 8.89 grams per cubic centimeter at 20°C shall apply.

Table 4.3-2 Characteristics of Mild Aluminum and Semi-hard Aluminum Wires

Diameter (mm)	Diameter tolerances (mm)	Sectional area (mm²)	Weight (kg/km)	Electric resistance 20°C (Ω/km)	Mild aluminum wire (A-Al) Tensile strength Max. (kg/mm²)	Mild aluminum wire (A-Al) Tensile strength Min. (kg/mm²)	Mild aluminum wire (A-Al) Tensile load Max. (kg)	Mild aluminum wire (A-Al) Tensile load Min. (kg)	Mild aluminum wire (A-Al) Elongation (per 250 mm) (%)	Semi-hard aluminum wire (HA-Al) Tensile strength Max. (kg/mm²)	Semi-hard aluminum wire (HA-Al) Tensile strength Min. (kg/mm²)	Semi-hard aluminum wire (HA-Al) Tensile load Max. (kg)	Semi-hard aluminum wire (HA-Al) Tensile load Min. (kg)	Semi-hard aluminum wire (HA-Al) Elongation (per 250 mm) (%)
5.0	±0.04	19.64	53.03	1.44	10.0	6.0	196	118	20	14.06	10.55	276	207	2.0
4.5	±0.04	15.90	42.93	1.78	10.0	6.0	159	95.4	20	14.06	10.55	224	168	2.0
4.3	±0.04	14.52	39.20	1.95	10.0	6.0	145	87.1	20	14.06	10.55	204	153	2.0
4.2	±0.04	13.85	37.40	2.04	10.0	6.0	139	83.1	20	14.06	10.55	195	146	2.0
4.0	±0.04	12.57	33.94	2.25	10.0	6.0	126	75.4	20	14.06	10.55	177	133	1.9
3.8	±0.04	11.37	30.62	2.49	12.0	7.0	136	79.6	20	14.06	10.55	160	120	1.9
3.7	±0.04	10.75	29.03	2.63	12.0	7.0	129	75.3	20	14.06	10.55	151	113	1.8
3.5	±0.04	9.621	25.98	2.94	12.0	7.0	116	67.4	20	14.06	10.55	135	102	1.7
3.2	±0.04	8.042	21.71	3.51	12.0	7.0	96.5	56.3	20	14.06	10.55	113	84.8	1.7
3.1	±0.04	7.548	20.38	3.75	12.5	7.0	94.4	52.8	18	14.06	10.55	106	79.6	1.6
2.9	±0.03	6.605	17.83	4.28	12.5	7.0	82.6	46.2	18	14.06	10.55	92.9	69.7	1.6
2.8	±0.03	6.158	16.63	4.59	12.5	7.0	77.0	43.1	18	14.06	10.55	86.6	65.0	1.5
2.6	±0.03	5.309	14.33	5.32	12.5	7.0	66.4	37.2	18	14.06	10.55	74.6	56.0	1.5
2.3	±0.03	4.155	11.22	6.80	12.5	7.0	51.9	29.1	18	14.06	10.55	58.4	43.8	1.5
2.0	±0.03	3.142	8.483	9.00	12.5	7.0	39.3	22.0	16	14.06	10.55	44.2	33.1	1.4
1.8	±0.03	2.545	6.872	11.1	12.5	7.0	31.8	17.8	16	14.06	10.55	35.8	26.8	1.4
1.6	±0.03	2.011	5.430	14.1	12.5	7.0	25.1	14.1	16	14.06	10.55	28.3	21.2	1.3
1.4	±0.03	1.539	4.155	18.4	13.0	7.0	20.0	10.8	14	14.06	10.55	21.6	16.2	1.2
1.2	±0.03	1.131	3.054	25.0	13.0	7.0	14.7	7.92	14	14.06	10.55	15.9	11.9	1.0
1.0	±0.03	0.7854	2.121	36.0	13.5	7.0	10.6	5.50	12	14.06	10.55	11.0	8.29	1.0
0.90	±0.02	0.6362	1.718	44.4	13.5	7.0	8.59	4.45	12	14.06	10.55	8.94	6.72	1.0
0.80	±0.02	0.5027	1.357	56.2	13.5	7.0	6.79	3.52	12	14.06	10.55	7.07	5.31	1.0
0.70	±0.02	0.3848	1.039	73.4	14.0	7.0	5.39	2.69	10					
0.65	±0.02	0.3318	0.8959	85.2	14.0	7.0	4.65	2.32	10					
0.60	±0.02	0.2827	0.7633	100	14.0	7.0	3.96	1.98	10					
0.55	±0.02	0.2376	0.6415	119	14.0	7.0	3.32	1.66	10					
0.50	±0.01	0.1964	0.5303	144	14.0	7.0	2.75	1.38	10					
0.45	±0.01	0.1590	0.4293	178	14.0	7.0	2.22	1.11	10					
0.40	±0.01	0.1257	0.3394	225	14.0	7.0	1.76	0.880	10					
0.35	±0.01	0.09621	0.2598	294	14.0	7.0	1.35	0.674	10					
0.32	±0.01	0.08042	0.2171	351	14.0	7.0	1.13	0.563	10					
0.29	±0.01	0.06605	0.1783	428	14.0	7.0	0.925	0.462	10					
0.26	±0.01	0.05309	0.1433	532	14.0	7.0	0.743	0.372	10					

(Note)
1. The aluminum wire is to have a conductivity of 61%.
2. Sectional area, weight, electric resistance and tensile load given in the table above relate to standard values.

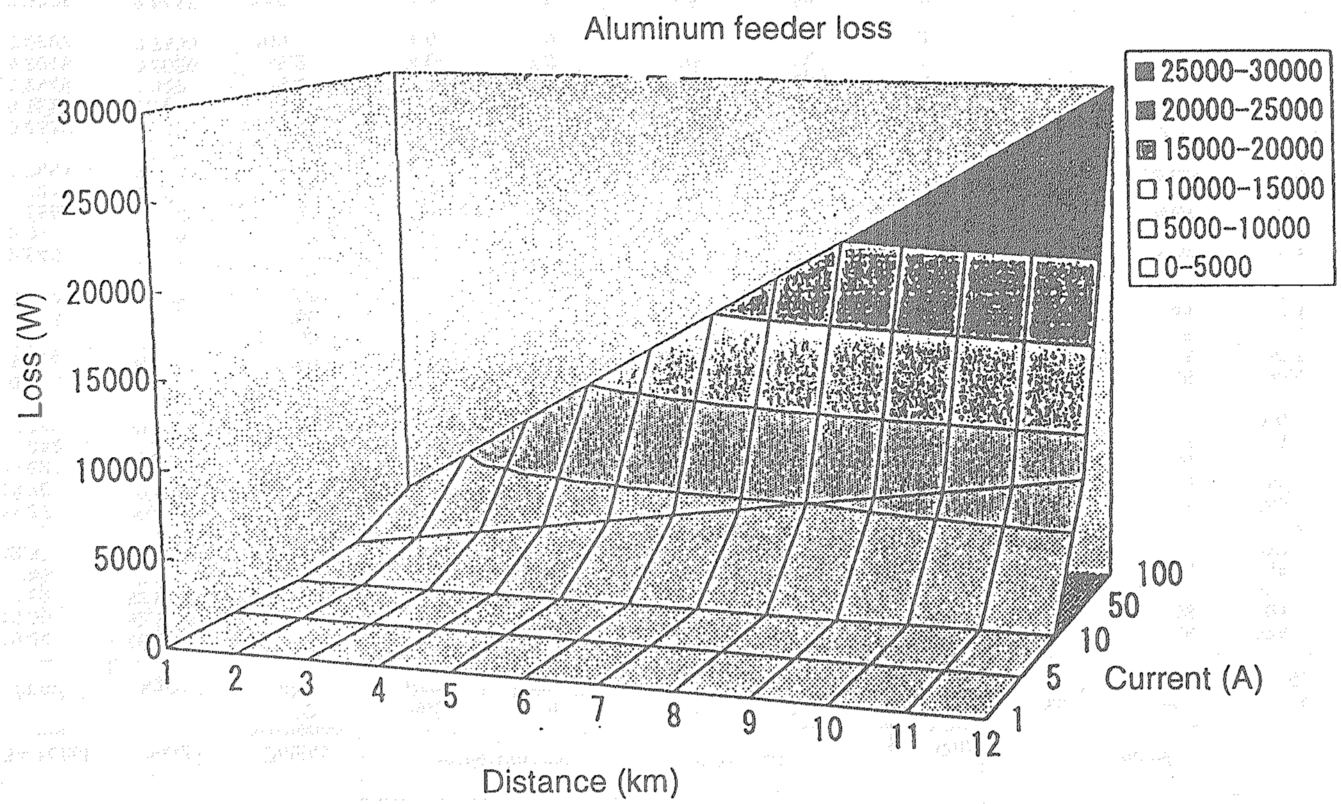


Fig. 4.3-1 Loss in Aluminum Feeder (diameter 12mm)

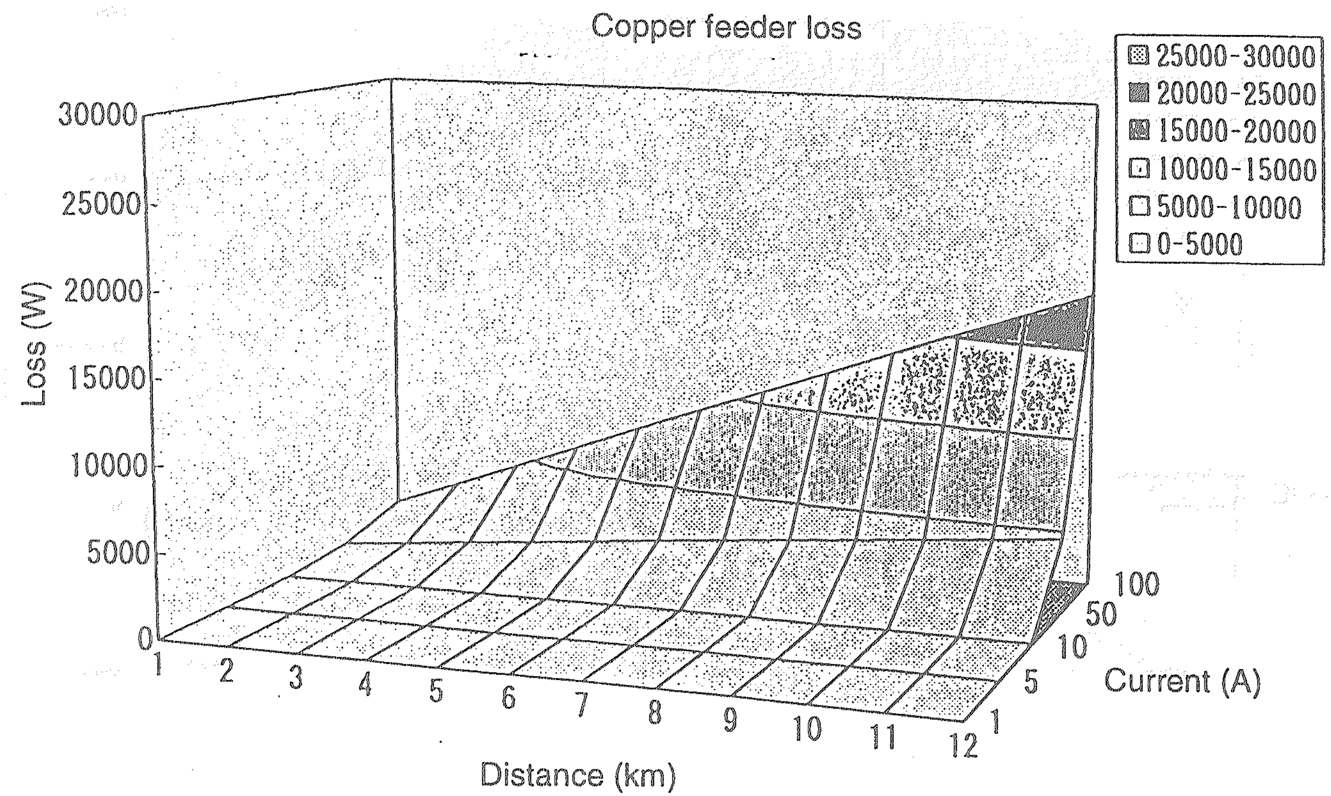


Fig. 4.3-2 Loss in Copper Feeder (diameter 12mm)

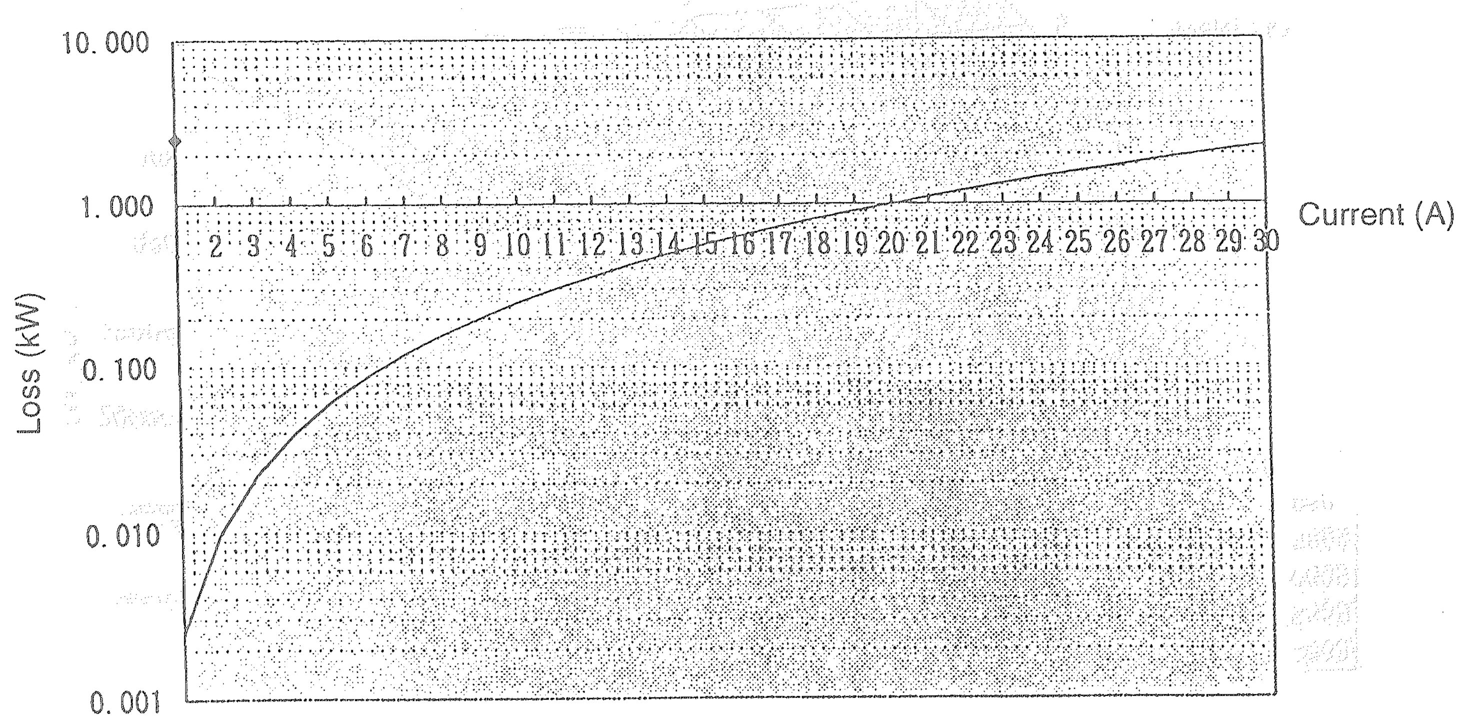


Fig. 4.3-3 Feeder Current vs. Loss (aluminum feeder, diameter 12mm and distance 20 km)

5. Studying a Power Receiving System

5.1 Studying a Power Receiving Area

CCIR-Rep.679 specifies the power transmission efficiency between power transmitting/ receiving antennas in a space power transmission system. Where the antennas are located face to face, the power transmission efficiency may be obtained from the curves given in Fig. 5.1-1 (Reference 1). In these curves, τ may be obtained with the following expression:

$$\tau = \frac{\sqrt{A_r A_t}}{\lambda Ds}$$

where

Ar : Area of the power receiving antenna
At : Area of the power transmitting antenna (diameter 9 km, circular)
λ : Wavelength (frequency 2.45GHz)
Ds : Distance between power transmitting and receiving antennas

From the figure, it may be gathered that the power can be transmitted approximately 100% with $\tau = 2.5$ or more. A power receiving area may be obtained from the power transmission efficiency which is one of the target design values. Table 5.1-1 shows the power receiving areas corresponding to $\tau = 0.5$, 1.0, 1.5, 2.0 and 2.5. In the study below, discussions will proceed on the assumption that $\tau = 1.5$. In this case, meanwhile, the power receiving area is obtainable from the following parameters relating to the glass ocean:

$\tau = 1.5$
$At = (4.5\times10^3)^2\times\pi = 63.6\times10^6$ (m^2)
$\lambda = 0.122$ (m)
Ds = 384,500 (km)
$Ar = 78.5\times10^6$ (m^2) $= (5\times10^3)^2\times\pi$ (m^2)

From Fig. 5.1-1, we can get a space transmission efficiency of 89% with $\tau = 1.5$. Where power transmitting and receiving antennas are positioned face to face, a space transmission loss of 11% can be achieved by providing power receiving equipment which covers a radius of 5 kilometers.

An SPS on the stationary orbit, however, requires the same power-incoming area as that calculated above to satisfy the above-mentioned requirements to locate the power transmitting and receiving antennas face to face. In the case of the glass ocean, however, the rotation of the earth on its axis changes the angle at which the power receiving antenna on the earth looks at the moon with the passage of time. If the power receiving antenna itself has a tracking function, therefore, it is necessary to increase the power receiving area. Now, assume that the power is received at an incident angle of 45 degrees. Then, it will be necessary to provide twice the power receiving area.

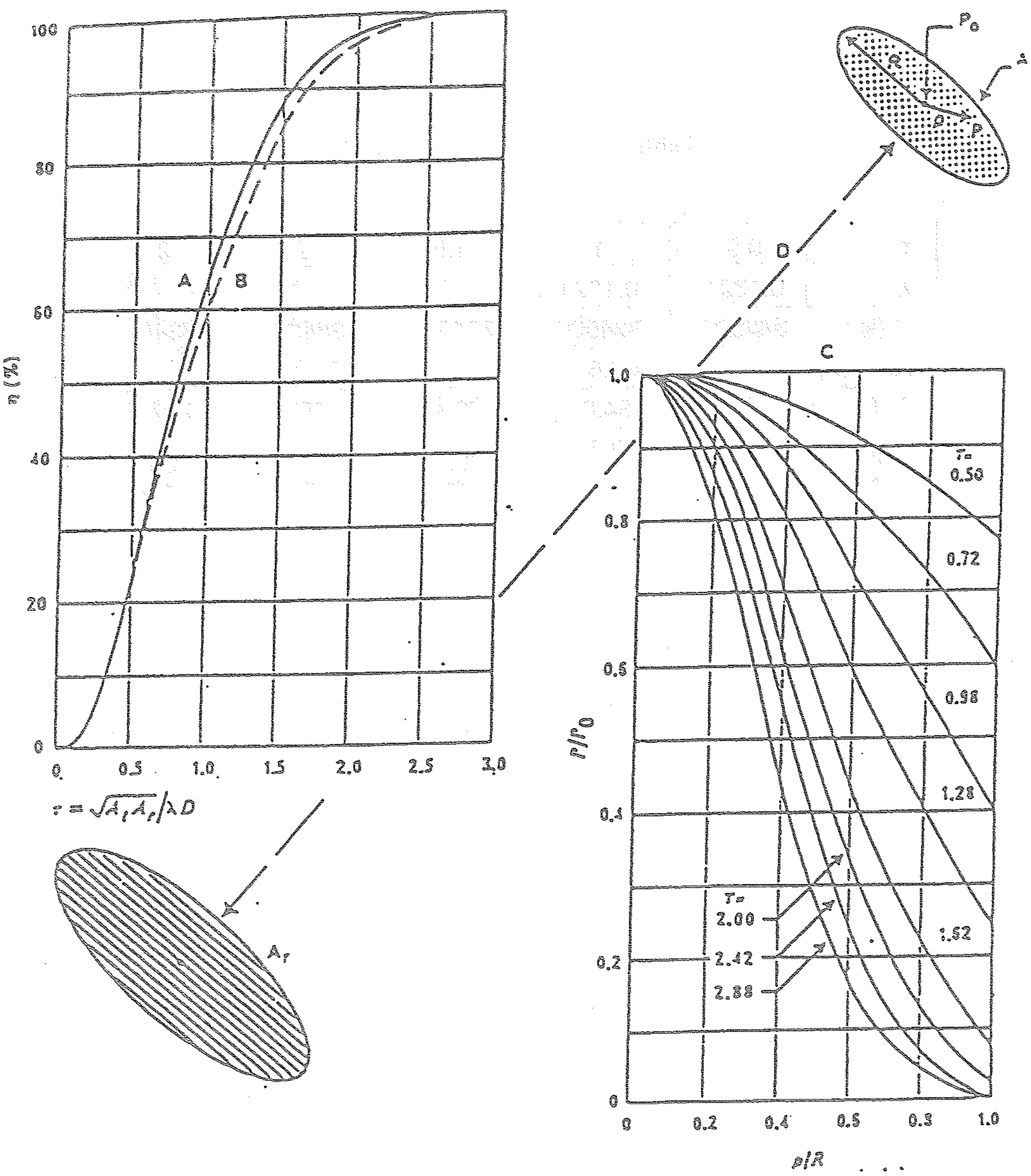


FIGURE 1 - *RF power beam transmission efficiency*

A : Circular aperture

B : Quadratic apertures

C : Optimum aperture taper

P_o: Power flux-density at the centre of the aperture

P : Power flex-density at the edge of the aperture

R : Radius of the aperture

ρ : Radius to a point on the aperture

η : Efficiency

Fig. 5.1-1 Transmission Efficiency in Microwave Power Transmission (CCIR-Rep.679)

Table 5.1-1 Power receiving Area

τ	0.5	1	1.5	2	2.5
λ	0.1224	0.1224	0.1224	0.1224	0.1224
D (km)	384500	384500	384500	384500	384500
At (km^2)	63.617	63.617	63.617	63.617	63.617
Ar (km^2)	8.71	34.84	78.40	139.38	217.78
Rr (km)	1.67	3.33	5.00	6.66	8.38
η (%)	22	64	89	97	100

Reference 1: Characteristics and Effects of Radio Techniques for The Transmission of Energy from Space, Report 679-2, CCIR

5.2 Studying a Collector/Distributor System

The rectenna will have a configuration nearly identical with that in the reference system. A brief study has been made here into the collector network for rectennas. The rectenna collector system shown in Fig. 5.2-1 has been proposed in the reference system. Where two panels are used to receive and collect a power of 14.8MW, approximately 5MW will flow through one cable. Rectenna elements are capable of generating a high voltage if connected in series. If they are so connected as to have an output of 40kV, for example, a current of 125 amperes will be available. The higher the voltage, the more the current will decrease. And it will also be possible to reduce the loss in the power transmission cable. Even at 125 amperes, however, the $1cm^2$ copper cable identical with the power transmission line to households, if used, allows us to obtain a resistance of 0.85 ohms at a length of 5 kilometers and a voltage drop of 106 volts so that the loss will be limited to 2.6%. In this case, the cable weighs 4.45 tons.

A rectenna's efficiency varies with a fluctuation of load. This load fluctuation, however, may be normally controlled to the optimum condition by means of an inverter as shown in Fig. 5.2-2 so that the maximum power can be drawn out of the rectenna. In other words, the inverter will automatically control the output voltage even if the load should fluctuate. And the full power will have to be output at that load. If an excess power should be produced, it will be regulated in the thermal power plant which allows output to be adjusted with ease. These technologies, including an inverter, etc. have been developed in a photovoltaic system on the earth, and they can be directly applied.

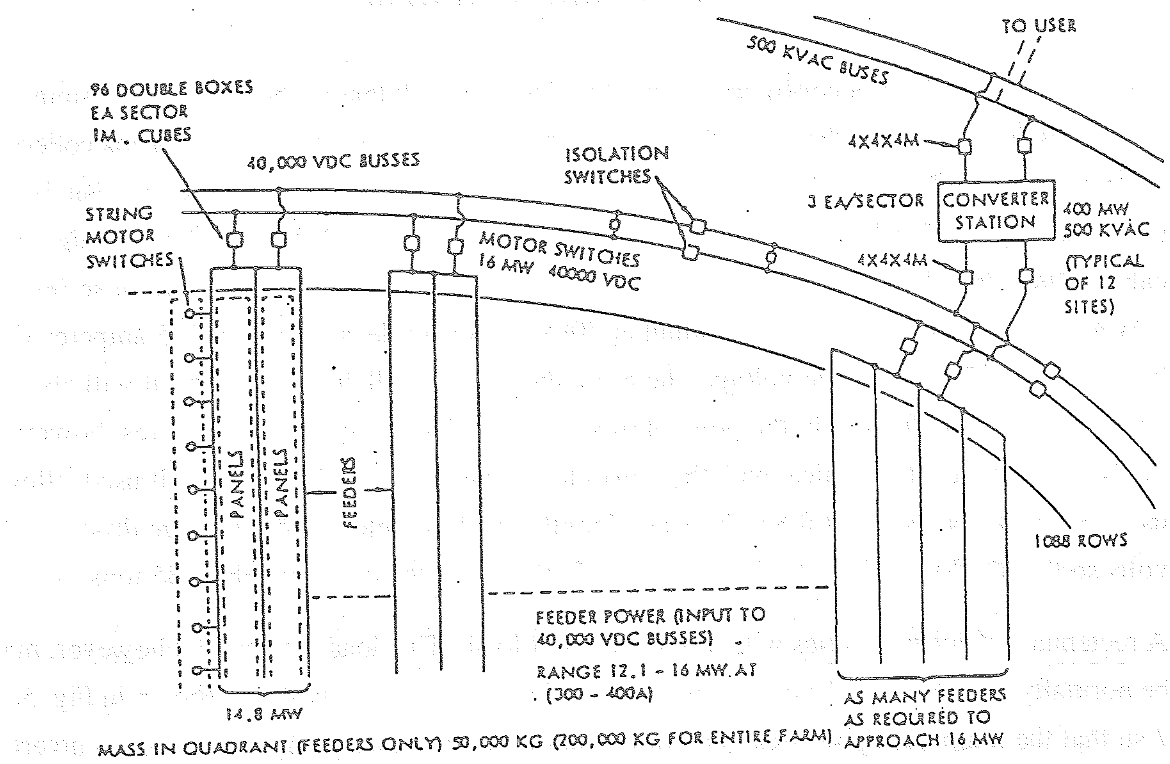
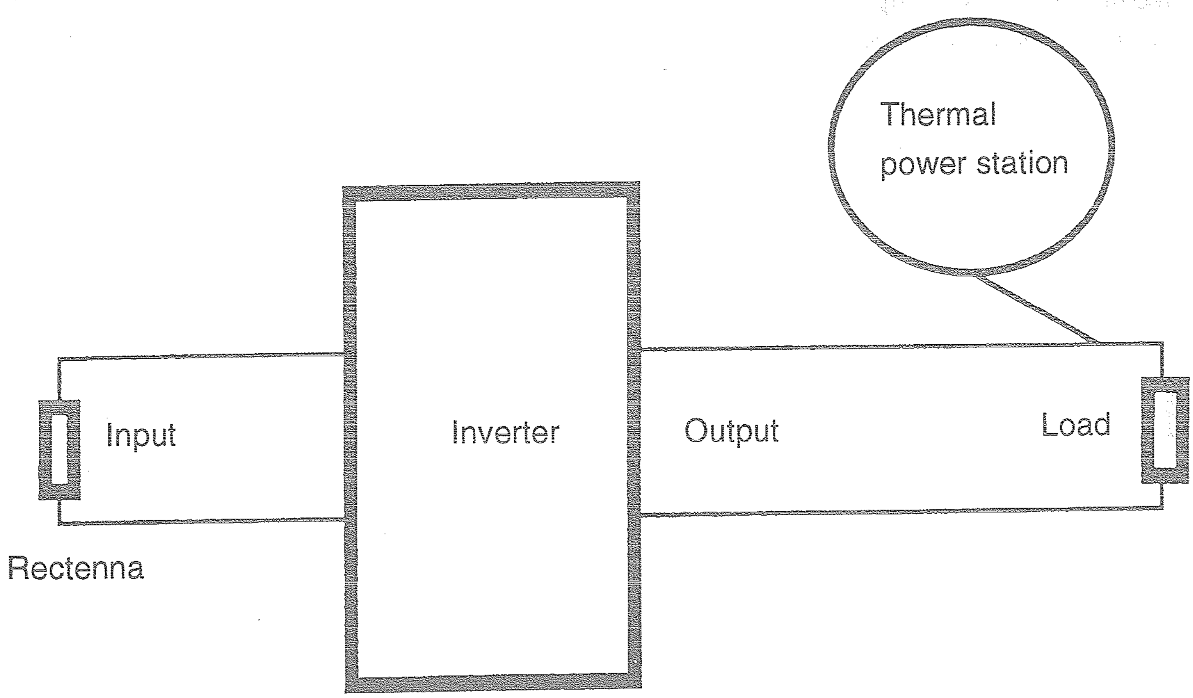


Fig. 5.2-1 Network to Collect Power in Rectennas



- Regulate an output voltage to a constant value.
- A load fluctuation is regulated by a thermal power station.

Fig. 5.2-2 How to Regulate a Load in a Rectenna

6. Studying a Distribution of Systems

With the above-mentioned study findings taken into account, a total power-generating, -transmitting and -receiving system is assumed as shown in Fig. 6-1. In this assumed system, it is necessary to take into consideration the loss items as described below. In the present study, meanwhile, the power generating capacity available in the glass ocean is taken to be the reference. It is necessary, therefore, to separately estimate the system's heat-collecting efficiency, etc.

6.1 Grounds of Loss Items

The grounds of each item are shown below.

6.1.1 Working Power in Sub-array Control System

Described herein is the power consumed in the receiver, phase detector, computer, and phase shifter driver circuit, all required to control the phase of a power-transmitting antenna. In the power-transmitting antenna, the phase is controlled on a sub-array by sub-array basis. This power requirement, therefore, is to be reckoned on a sub-array by sub-array basis. Here a power of 50 Watts is distributed to the sub-arrays and presumably broken down into 15W for the receiver, 5W for the phase detector, 20W for the computer and 10W for the phase shifter driver circuit.

6.1.2 Feeder Loss (DC)

This loss is the power consumed due to the electric resistance in the feeder from the glass ocean to a sub-array. A loss of 10 thru 15% has been allocated here to the power cable on the earth. In the present system, however, a loss of 1% is allocated because it is necessary to reduce the power transmission distance and to increase the efficiency.

6.1.3 Power Conversion Efficiency (SSPA Efficiency)

This efficiency relates to the conversion of dc power to a high-frequency one. The existing SSPA in the 2GHz band has a conversion efficiency of approximately 40% at the maximum though it varies with the operation of an amplifier. A power conversion efficiency of 50% is herein allocated while being expected to increase along with the progress of technology in the future.

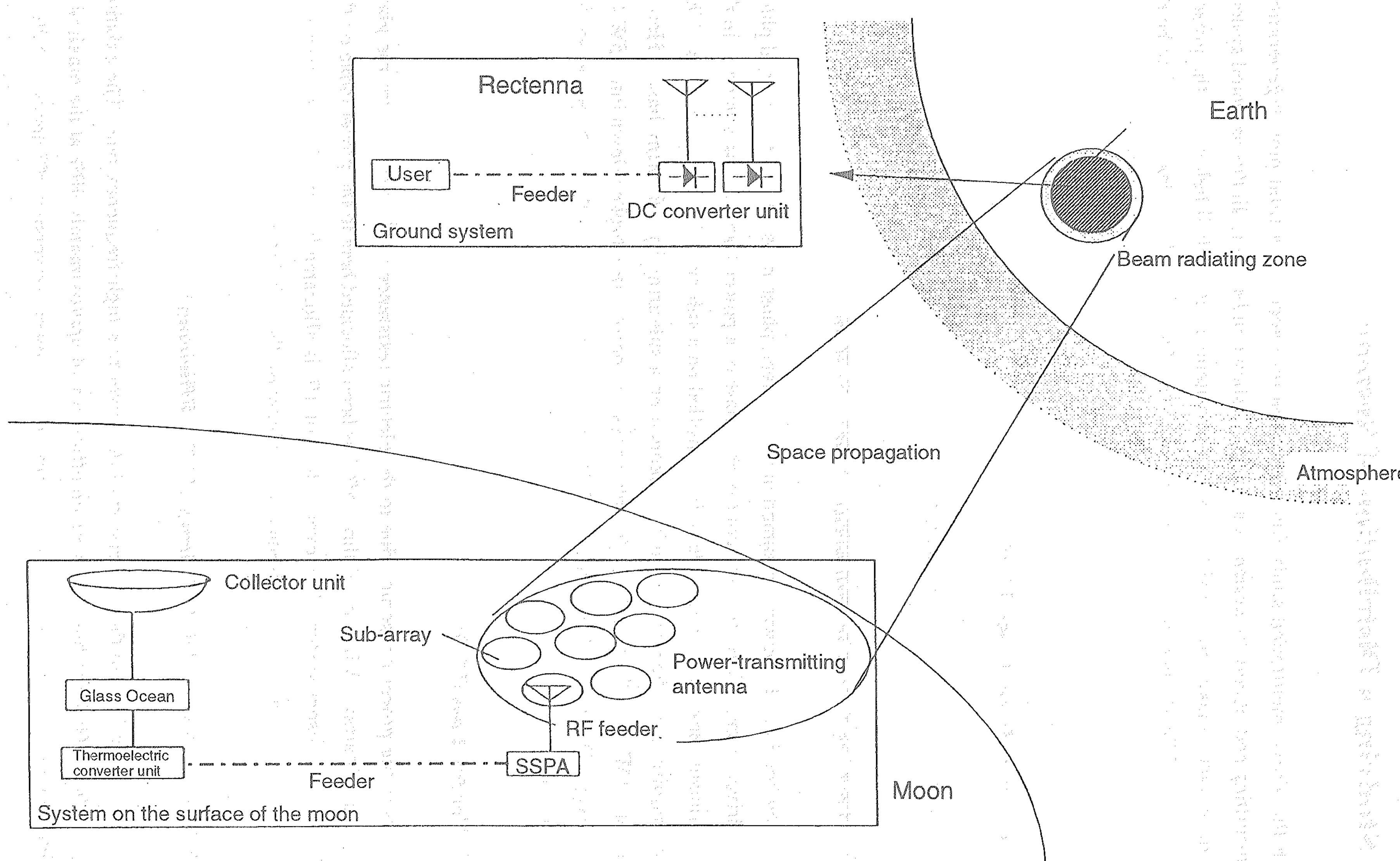


Fig. 6-1 Overall Glass Ocean System Configuration

6.1.4 Feeder Loss (RF)

This loss is generated in the feeder and filter of the SSPA-converted high-frequency power to the antenna at the end. In a communication system, a loss of 1 thru 3dB (20 thru 50%) is reckoned generally. With a filter or the like inserted, moreover, the loss remains at approximately 0.5 thru 1dB (10 thru 20%).

In this case, a loss of 5% (0.2dB) is allocated, considering that the SSPA is located just under the antenna.

6.1.5 Space Propagation Loss

This loss is represented by the value indicating to what extent a power-receiving antenna is capable of receiving the radio waves radiated from a power-transmitting antenna. This value is dependent upon the areas of both power-transmitting and -receiving antennas, distance between both and wave-length. Here a loss of 95% is allocated. What size a power-receiving antenna should have to satisfy the value so allocated will be studied separately.

6.1.6 Atmosphere Absorption Loss

This is the loss of electromagnetic waves absorbed in the atmosphere around the earth. Generally, the atmosphere absorption loss increases as the frequency gets higher. Fig. 6.1-1 (Reference 1) shows the relationship between frequency and attenuation. From this figure, it may be gathered that a frequency of 2.45GHz studied for the present system attenuates at a rate of 0.2dB per kilometer (1 atm.). In the case of a frequency which has arrived from space, it is necessary to take into consideration both propagation length in the atmosphere and air pressure. Here, however, it is assumed that the overall propagation length is reckoned at 1 atm., and that the propagation distance is 1 kilometer (because the atmosphere decreases, too, although the propagation distance is really a little longer). And a loss of 5% is allocated.

6.1.7 Rectenna's Energy Collecting Efficiency

This efficiency is represented by the value indicating to what extent the antenna element of a rectenna, or power-incoming antenna, is capable of collecting the radiated energy. A rectenna energy collecting efficiency of 88% is allocated. This is the NASA SPS reference model value.

6.1.8 Rectenna's Energy Conversion Efficiency

This efficiency is represented by the value indicating to what extent a rectifier element is capable of converting to electricity the energy collected by the rectenna, power-receiving antenna.

6.1.9 Power Transmission Network Conversion Efficiency

This efficiency is represented by the value indicating how efficiently the system is capable of transmitting to a power transmission network the power which has been collected by the rectenna, power-receiving antenna, and converted to energy by the rectifier element. A power transmission network conversion efficiency of 97% is allocated here. This is the NASA SPS reference model value.

Reference 1: CCIR Rep.719

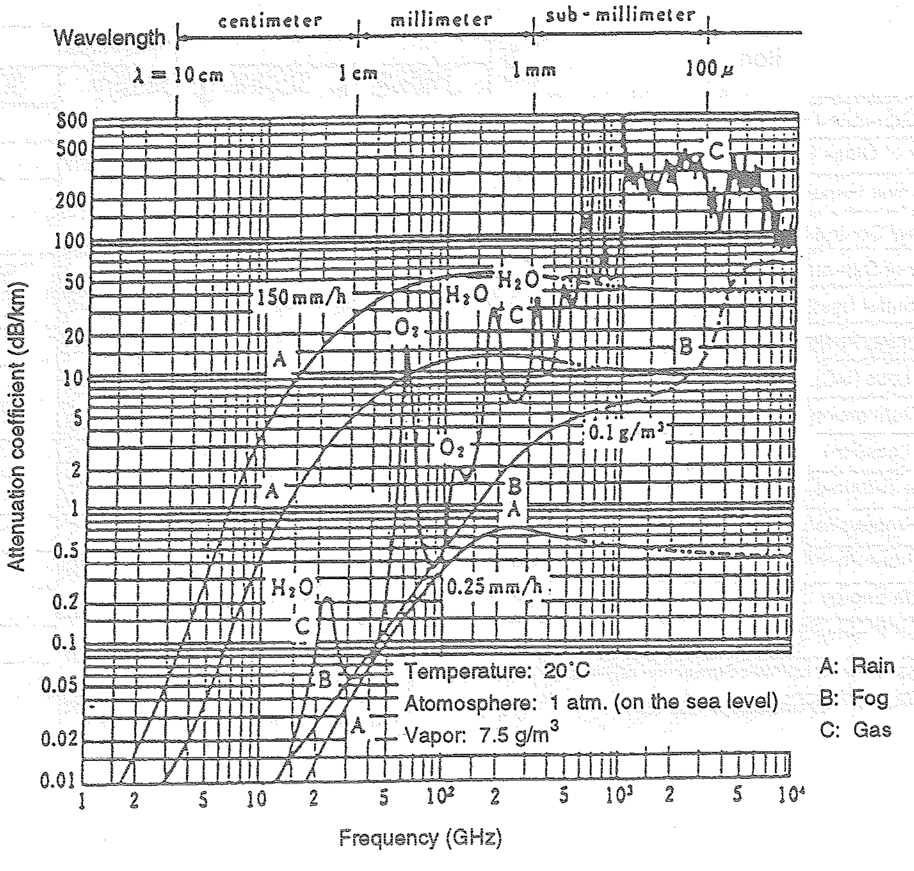


Fig. 6.1-1 Radio Wave Attenuation Curves (CCIR-Rep. 719)

6.2 Loss Allocation Chart

Table 6.2-1 shows the results of allocating the loss, based on the findings mentioned above. Eventually, it has been found that a 100kW glass ocean system requires 109,626 ones.

Table 6.2-1 Glass Ocean Loss Allocation Chart

Item	Unit	Glass Ocean				
		100kW	300kW	500kW	800kW	1000kW
Power Generated in One Glass Oceans	kW	100	300	500	800	1000
Number of Glass Oceans		109626	36542	21925	13703	10963
Total Power Generated in Glass Oceans	GW	11.0	11.0	11.0	11.0	11.0
Sub-array Control System Working Power	W	50	50	50	50	50
Number of Sub-arrays		6600000	6600000	6600000	6600000	6600000
Total Control System Working Power	GW	0.33	0.33	0.33	0.33	0.33
Transmitting Power	GW	10.6	10.6	10.6	10.6	10.6
Feeder Loss (DC)	ND	0.99	0.99	0.99	0.99	0.99
Power Conversion Efficiency	ND	0.50	0.50	0.50	0.50	0.50
Feeder Loss(RF)	ND	0.95	0.95	0.95	0.95	0.95
Antenna Terminal Transmitting Power	GW	5	5	5	5	5
Space Propagation Loss	ND	0.98	0.98	0.98	0.98	0.98
Atmosphere Absorption Loss	ND	0.95	0.95	0.95	0.95	0.95
Rectenna Energy Collecting Efficiency	ND	0.88	0.88	0.88	0.88	0.88
Rectenna Energy Conversion Efficiency	ND	0.89	0.89	0.89	0.89	0.89
Transmission Power Network Conversion Efficiency	ND	0.97	0.97	0.97	0.97	0.97
Transmission Network Supply Power	GW	3.7	3.7	3.7	3.7	3.7

7. Studying Reliability and Maintenance

To what extent maintenance is required will be calculated here concerning a gigantic group of sub-arrays employed in a power-transmitting system for a lunar energy system aimed at transmitting electric power to the earth.

For an output of 5GW to materialize, 6.6 million sub-arrays are to be installed on the surface of the moon, with each sub-array composed of seventy-six 10W SSPAs (an equilateral hexagon inscribed in a ø3.5m circle). In other words, a total of more than 5 hundred million SSPAs exist in this system. If each SSPA (subsystem in the periphery of each amplifier) should have a failure rate of 1000FIT, for example, a simple integration would allow us to gather that more than 500 SSPAs will fail hourly. Considering that the overall system has a diameter of approximately 10 kilometers, we must realize its maintenance will involve great difficulties.

From the viewpoint of ease of maintenance, therefore, we have here adopted a policy of replacing the SSPAs on a sub-array by sub-array basis. On the assumption that the output of each sub-array is to be normally monitorable and that up to an arbitrary number of SSPAs in a sub-array are allowed to fail, to what extent maintenance will be required (number of SPPAs required to be replaced per unit time) is clarified hereunder.

In the case studied below, the maintenance policy taken is such that each sub-array should be replaced with a new one immediately after more than an arbitrary number of amplifiers in the sub-array have failed. The time required for maintenance (replacement) is to be reckoned as zero. And it is assumed that those sub-arrays which failed at a certain Time t are to be replaced with new sub-arrays at Time t.

(1) Case where a sub-array is to be replaced if one or more of its elements has failed:

Discussed here is the maintenance policy of replacing a sub-array with a new one immediately after one amplifier or more in the sub-array has failed.

Assume that:

- λ : Failure rate of each amplifier (= 1000(FIT))
- P_{00} : Probability with which all 76 normal amplifiers remain normal after the lapse of a unit time,
- P_{01} : Probability with which one or more of the 76 normal amplifiers may fail after the lapse of a unit time,
- N_T : Total number of sub-arrays
- N : Number of sub-arrays (= 6.6E6) unless a redundant system is held
- N_d : Number of sub-arrays required to be replaced per unit time (1 hour).

Then,

$$P_{01} = 1 - P_{00}$$
$$P_{00} = \{\exp(-\lambda t)\}^{76} = 0.999924002$$

The total number of the sub-arrays required to allow for a decrease in output due to a failure is:

$$N_T = N \times \{76 / (76-1)\}$$

Therefore,

$$N_d = N_T \times P_{01} = 508.27 \qquad (7.1.1)$$

<Reference>

The policy taken is such that a redundant system is to be provided, based on not the total number of sub-arrays but the number of amplifiers in a sub-array.

$$N_d = N \times [1-\{\exp(-\lambda t)\}^{77}] = 508.18 \qquad (7.1.2)$$

Thus, there is not such a significant difference between (7.1.1) and (7.1.2).

(2) Case where a sub-array is to be replaced if two or more of its elements have failed:

(a) Estimating the number of sub-arrays to be replaced at Time t:

If one amplifier is allowed to fail after the lapse of Time t, obtain the number of sub-arrays in each of which two or more amplifiers will fail after the lapse of t + 1 hour. All of the sub-arrays, each of which has two or more amplifiers failed then (by Time t), are assumed to be replaced with the sub-arrays which have not failed.

Set parameters as follows:

- λ : Failure rate of each amplifier (= 1000(FIT))
- λ_t : Failure rate of each amplifier by Time t
- P_{t01} : Probability with which one of the 76 normal amplifiers may fail after the lapse of Time t,
- P_{02} : Probability with which two or more of the 76 normal amplifiers may fail after the lapse of a unit time,
- P_{11} : Probability with which one or more of the 75 normal amplifiers may fail after the lapse of a unit time,
- N_T : Total number of sub-arrays
- N : Number of sub-arrays (= 6.6E6) unless a redundant system is held
- N_0 : Number of sub-arrays, each of which has every amplifier remain normal at Time t
- N_1 : Number of sub-arrays, each of which has had one amplifier failed at Time t
- N_d : Number of sub-arrays, each of which has two or more amplifiers failed between Time t and t + 1 hour (number of sub-arrays required to be replaced at t + 1 hour)

A total number of the sub-arrays required to allow for a decrease in output due to a failure is:

$$N_T = N \times \{76 / (76-2)\}$$

It is assumed that N_0 contains those sub-arrays, each of which has two or more amplifiers failed and replaced with normal ones, and those which have not failed to begin with. Therefore, we can get:

$$N_0 = N_T - N_1$$

Then,

$$N_1 = N_T \times P_{t01}$$

$$P_{t01} = 76 \times (1 - \lambda_t)^{75} \times \lambda_t$$

$$P_{02} = 1 - \{(1 - \lambda)^{76} + 76 \times (1 - \lambda)^{75} \times \lambda\}$$

And we can get N_d as follows:

$$N_d = N_0 P_{02} + N_1 P_{11}$$

(Example)

With t = 8760(h),

$\lambda_t = 8.72E\text{-}3$

$N_1 = 2.33E6$, $N_0 = 4.45E6$

$N_d = 177.03 \rightarrow$ 177 sub-arrays need be replaced hourly.

(b) Expression by a Gradually Changing Formula

Discussed here is how the ratio of sub-arrays in the Failure 1 mode to those in the Failure 0 mode in a total number of sub-arrays changes, with the passage of Time t.

The sub-arrays composed of the amplifiers that are all normal upon starting will be divided after the lapse of a unit time into the following three groups:

- Sub-arrays with all amplifiers normal,
- Sub-arrays, each of which has one amplifier failed, and
- Sub-arrays, each of which has two or more amplifiers failed.

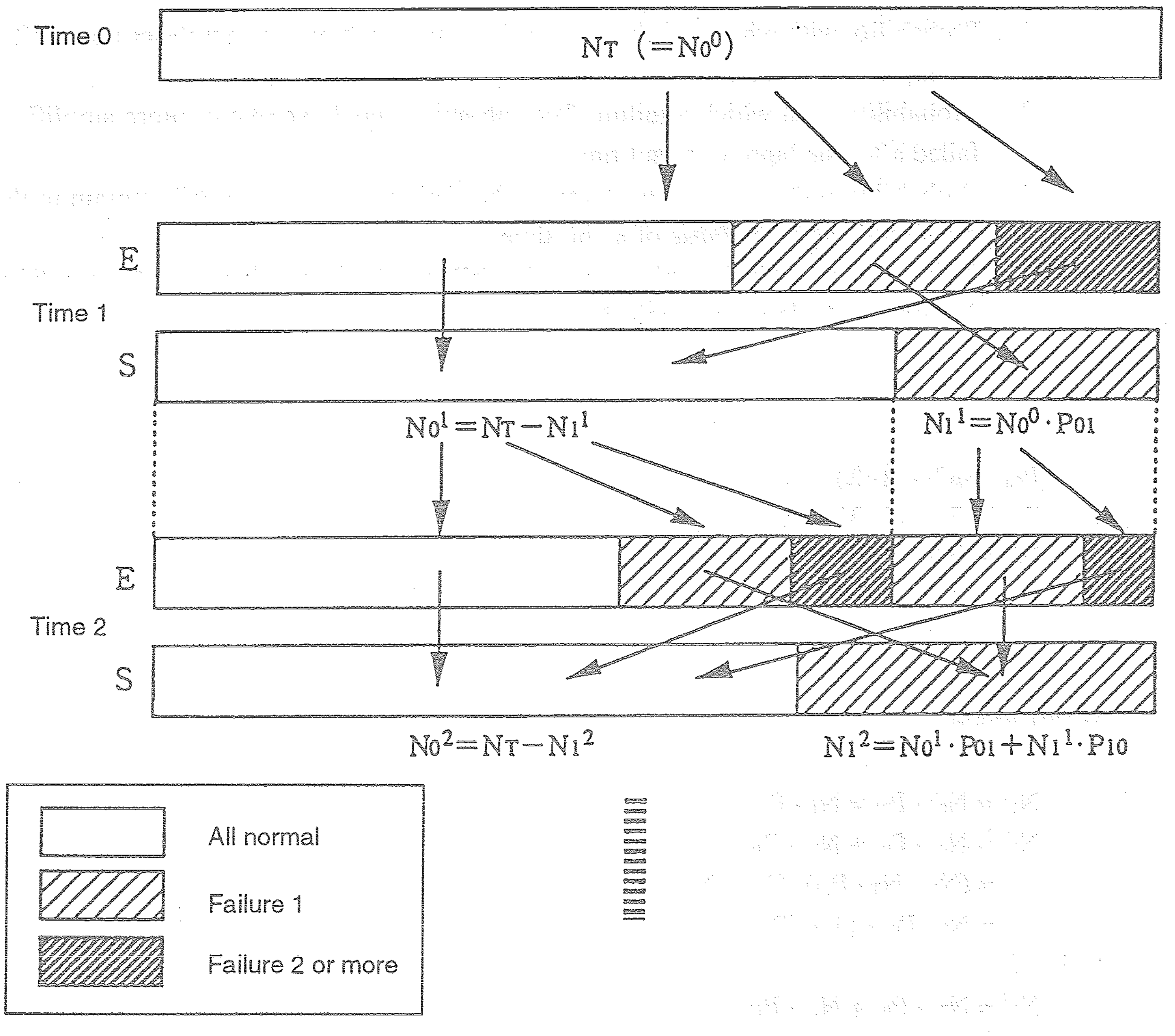
In this case, it is assumed that the time required for maintenance is not taken into consideration and that any sub-array with two or more amplifiers failed is immediately replaced with a new sub-array. In other words, after the lapse of Arbitrary Time t, a start will be made in either of the following two modes:

- All normal
- Failure 1.

After the lapse of a unit time, furthermore, the mode will change as follows:

- All normal → • All normal / • Failure 1 / • Failure 2 or more
- Failure 1 → • Failure 1 / • Failure 2 or more

These mode changes may be illustrated as follows:



Now, it is assumed that upon starting at Time n (after completion of maintenance):

N_T : Total number of sub-arrays
N_1^n : Number of sub-arrays, each of which has one amplifier failed
N_0^n : Number of sub-arrays free from failure

In each of the cases referred to above, the probability is to be set as follows:

P_{00}: Probability with which a failure-free sub-array may remain free from failure after the lapse of a unit time

P_{01}: Probability with which a failure-free sub-array may have one amplifier failed after the lapse of a unit time

P_{02}: Probability with which a failure-free sub-array may have two or more amplifiers failed after the lapse of a unit time

P_{10}: Probability with which a sub-array in the Failure 1 mode may still remain in the same mode after the lapse of a unit time

P_{11}: Probability with which a sub-array in the Failure 1 mode may have another amplifier failed after the lapse of a unit time

where

$$P_{00} = {}_{76}C_0 \cdot (1-\lambda)^{76}$$
$$P_{01} = {}_{76}C_1 \cdot (1-\lambda)^{75} \cdot \lambda$$
$$P_{10} = {}_{75}C_0 \cdot (1-\lambda)^{75}$$
$$P_{02} = 1 - P_{00} - P_{01}$$
$$P_{11} = 1 - P_{10}$$

As illustrated,

$$N_1^1 = N_0^0 \cdot P_{01} = N_T \cdot P_{01}$$
$$\begin{aligned} N_1^2 &= N_0^1 \cdot P_{01} + N_1^1 \cdot P_{10} \\ &= (N_T - N_T \cdot P_{01}) \cdot P_{01} + N_T \cdot P_{01} \cdot P_{10} \\ &= N_T \cdot P_{01} \cdot \{1 + (P_{10} - P_{01})\} \end{aligned}$$

And

$$\begin{aligned} N_1^3 &= N_0^2 \cdot P_{01} + N_1^2 \cdot P_{10} \\ &= N_T \cdot P_{01} + N_1^2 \cdot (P_{10} - P_{01}) \\ &= N_T \cdot P_{01} \cdot \{1 + (P_{10} - P_{01}) + (P_{10} - P_{01})^2\} \end{aligned}$$

Likewise, we can get:

$$N_1^n = N_T \cdot P_{01} \cdot \sum_{k=1}^{n} (P_{10} - P_{01})^{k-1} \qquad (7.2.1)$$

Thus, it is possible to immediately obtain a ratio of sub-arrays in the Failure 1 mode to those in the Failure 0 mode in a total number of sub-arrays.

In addition, assume that Nd is the number of sub-arrays to be replaced at Time n during a unit time. Then, we can get:

$$N_d = (N_T - N_1^n) \cdot P_{02} + N_1^n \cdot P_{11}$$
$$= (N_T - N_1^n) \cdot (1 - P_{00} - P_{01}) + N_1^n \cdot (1 - P_{10})$$

(3) Case where a sub-array is to be replaced if three or more of its elements have failed:

Discussed here is the maintenance policy of replacing a sub-array with a new one once three amplifiers in the sub-array have failed while allowing two amplifiers in the sub-array to fail.

In each of the cases, set the probability as follows:

- P_{00} : Probability with which a failure-free sub-array may remain free from failure after the lapse of a unit time
- P_{01} : Probability with which a failure-free sub-array may have one amplifier failed after the lapse of a unit time
- P_{02} : Probability with which a failure-free sub-array may have two or more amplifiers failed after the lapse of a unit time
- P_{03} : Probability with which a failure-free sub-array may have three or more amplifiers failed after the lapse of a unit time
- P_{10} : Probability with which a sub-array in the Failure 1 mode may still remain in the same mode after the lapse of a unit time
- P_{11} : Probability with which a sub-array in the Failure 1 mode may have another amplifier failed after the lapse of a unit time
- P_{12} : Probability with which a sub-array in the Failure 1 mode may have another two amplifiers or more failed after the lapse of a unit time
- P_{20} : Probability with which a sub-array in the Failure 2 mode may still remain in the same mode after the lapse of a unit time
- P_{21} : Probability with which a sub-array in the Failure 2 mode may have another amplifier failed after the lapse of a unit time

where

$$P_{00} = {}_{76}C_0 \cdot (1 - \lambda)^{76}$$
$$P_{01} = {}_{76}C_1 \cdot (1 - \lambda)^{75} \cdot \lambda$$
$$P_{02} = {}_{76}C_2 \cdot (1 - \lambda)^{74} \cdot \lambda^2$$
$$P_{10} = {}_{76}C_0 \cdot (1 - \lambda)^{75}$$
$$P_{11} = {}_{75}C_1 \cdot (1 - \lambda)^{74} \cdot \lambda$$
$$P_{20} = {}_{74}C_0 \cdot (1 - \lambda)^{74}$$
$$P_{03} = 1 - P_{00} - P_{01} - P_{02}$$
$$P_{12} = 1 - P_{10} - P_{11}$$
$$P_{21} = 1 - P_{20}$$

As illustrated on this page, clarify the relations of sub-arrays in each of the modes at Time n - 1 and at Time 1, and we will be able to get a gradually changing formula as follows:

$$N_0^n = N_T - N_1^n - N_2^n$$

$$N_1^n = N_0^{n-1} \circ P_{01} + N_1^{n-1} \circ P_{10}$$

$$N_2^n = N_0^{n-1} \circ P_{02} + N_1^{n-1} \circ P_{11} + N_2^{n-1} \circ P_{20}$$

where

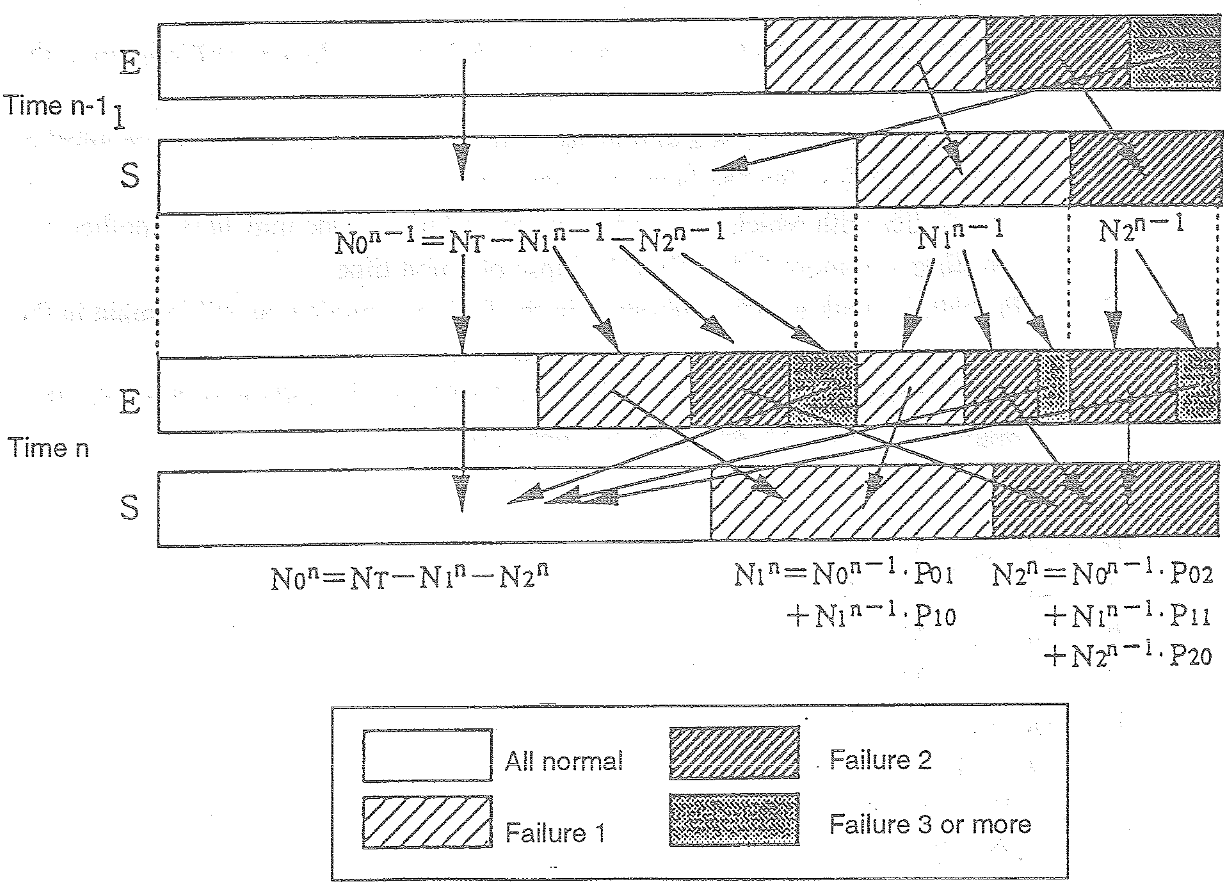
$$N_T = N \times \{76 / (76-3)\}$$

N_k^n : Number of sub-arrays, each of which has k-amplifiers failed upon start of Time n (after completion of maintenance)

If the number of sub-arrays to be replaced per unit time is reckoned as N_d:

We can get:

$$N_d = N_0^{n-1} \circ P_{03} + N_1^{n-1} \circ P_{12} + N_2^{n-1} \circ P_{21} \qquad (7.3.1)$$



(Supplement)

Concerning the maintenance policy of replacing a sub-array whose four amplifiers have failed while allowing three amplifiers in the sub-array to fail, it is possible, in exactly the same way, to obtain the number of sub-arrays required to be replaced per unit time (N_d) as follows:

$P_{00} = {}_{76}C_0 (1-\lambda)^{76}$:

Probability with which a failure-free sub-array may remain free from failure after the lapse of a unit time

$P_{01} = {}_{76}C_1 (1-\lambda)^{75} \cdot \lambda$:

Probability with which a failure-free sub-array may have one amplifier failed after the lapse of a unit time

$P_{02} = {}_{76}C_2 (1-\lambda)^{74} \cdot \lambda^2$:

Probability with which a failure-free sub-array may have two or more amplifiers failed after the lapse of a unit time

$P_{03} = {}_{76}C_3 (1-\lambda)^{73} \cdot \lambda^3$:

Probability with which a failure-free sub-array may have three or more amplifiers failed after the lapse of a unit time

$P_{10} = {}_{75}C_0 (1-\lambda)^{75}$:

Probability with which a sub-array in the Failure 1 mode may still remain in the same mode after the lapse of a unit time

$P_{11} = {}_{75}C_1 (1-\lambda)^{74} \cdot \lambda$:

Probability with which a sub-array in the Failure 1 mode may have another amplifier failed after the lapse of a unit time

$P_{12} = {}_{75}C_2 (1-\lambda)^{73} \cdot \lambda^2$:

Probability with which a sub-array in the Failure 1 mode may have another two amplifiers or more failed after the lapse of a unit time

$P_{20} = {}_{74}C_0 (1-\lambda)^{74}$:

Probability with which a sub-array in the Failure 2 mode may still remain in the same mode after the lapse of a unit time

$P_{21} = {}_{74}C_1 (1-\lambda)^{73} \cdot \lambda$:

Probability with which a sub-array in the Failure 2 mode may have another amplifier failed after the lapse of a unit time

$P_{30} = {}_{73}C_0 (1-\lambda)^{73}$:

Probability with which a sub-array in the Failure 3 mode may still remain in the same mode after the lapse of a unit time

$P_{04}=1-P_{00}-P_{01}-P_{02}-P_{03}$:

Probability with which a failure-free sub-array may have four or more amplifiers failed after the lapse of a unit time

$P_{13}=1-P_{10}-P_{11}-P_{12}$:

Probability with which a sub-array in the Failure 1 mode may have another three amplifiers or more failed after the lapse of a unit time

$P_{22}=1-P_{20}-P_{21}$:

Probability with which a sub-array in the Failure 2 mode may have another two amplifiers or more failed after the lapse of a unit time

$P_{31}=1-P_{30}$:

Probability with which a sub-array in the Failure 3 mode may have another amplifier or more failed after the lapse of a unit time

$$N_0^n = N_T - N_1^n - N_2^n - N_3^n$$
$$N_1^n = N_0^{n-1} \cdot P_{01} + N_1^{n-1} \cdot P_{10}$$
$$N_2^n = N_0^{n-1} \cdot P_{02} + N_1^{n-1} \cdot P_{11} + N_2^{n-1} \cdot P_{20}$$
$$N_3^n = N_0^{n-1} \cdot P_{03} + N_1^{n-1} \cdot P_{12} + N_2^{n-1} \cdot P_{21} + N_3^{n-1} \cdot P_{30}$$

where

$$N_T = N \times \{76 / (76-4)\}$$

N_k^n : Number of sub-arrays, each of which has k-amplifiers failed upon start of Time n (after completion of maintenance)

If the number of sub-arrays to be replaced per unit time is reckoned as N_d, we can get a gradually changing formula:

$$N_d = N_0^{n-1} \cdot P_{04} + N_1^{n-1} \cdot P_{13} + N_2^{n-1} \cdot P_{22} + N_3^{n-1} \cdot P_{31} \quad (7.3.2)$$

(4) Calculation and Consideration

Based on the gradually changing formulas found in (2) and (3) above, calculations are to be made herein concerning the time-oriented changes in the number of the sub-arrays that have to be replaced, based on each maintenance policy.

Fig. 7.1 shows how many sub-arrays need to be replaced hourly to maintain the system when the following four maintenance policies (to replace sub-arrays) are held:

- Replace the sub-array which has one element or more failed (Policy 1).
- Replace the sub-array which has two elements or more failed (Policy 2).
- Replace the sub-array which has three elements or more failed (Policy 3).
- Replace the sub-array which has four elements or more failed (Policy 4).

The axis of abscissas indicates the time that has elapsed after installing the system. Apart from in the policy of replacing a sub-array which has one element or more failed, those sub-arrays which have an allowable number of failures will increase with the passage of time. As a result, the number of sub-arrays that have to be replaced will also increase. After the lapse of 160 thousand hours, the number of sub-arrays to be replaced has nearly converged, irrespective of maintenance policy. This is because the number of sub-arrays with allowable failures in each failure mode becomes balanced. In other words, the number of sub-arrays increased and decreased after the lapse of a unit time becomes equalized in each failure mode.

The number of sub-arrays replaced after the lapse of 160 thousand hours (which has nearly converged) has been obtained as follows:

(Policy 1) $N_d(1) = 508.27$ pieces
(Policy 2) $N_d(2) = 255.87$ pieces
(Policy 3) $N_d(3) = 171.76$ pieces
(Policy 4) $N_d(4) = 129.72$ pieces

Fig. 7.2 shows the changes in ratio of the number of sub-arrays comprising normal amplifiers under each of the policies to the total of sub-arrays as a whole. The ratios after the lapse of 160 thousand hours have been obtained as follows:

(Policy 1) 1.0000
(Policy 2) 0.4967
(Policy 3) 0.3289
(Policy 4) 0.2450

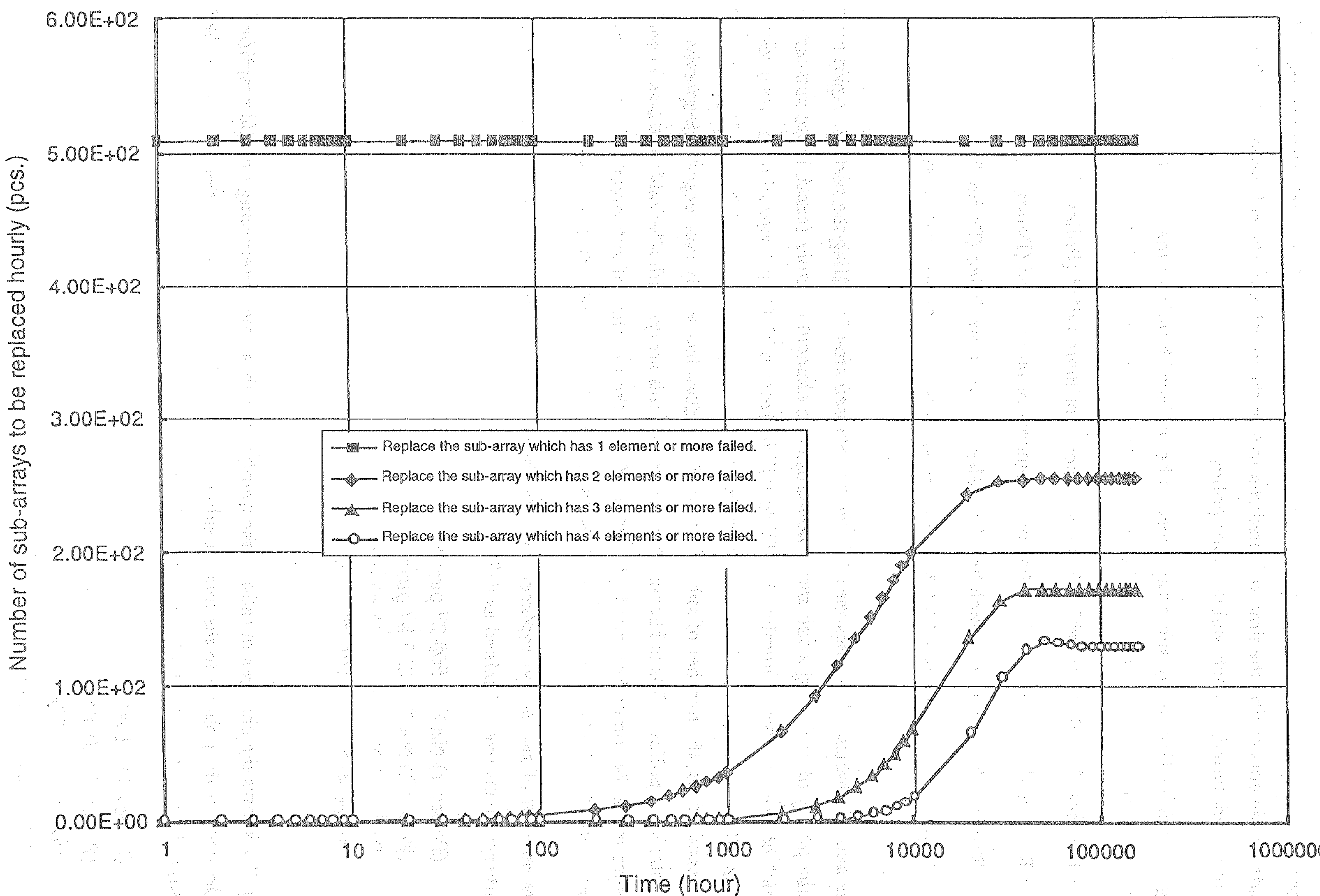


Fig. 7.1 Number of Sub-arrays to be Replaced (per hour)

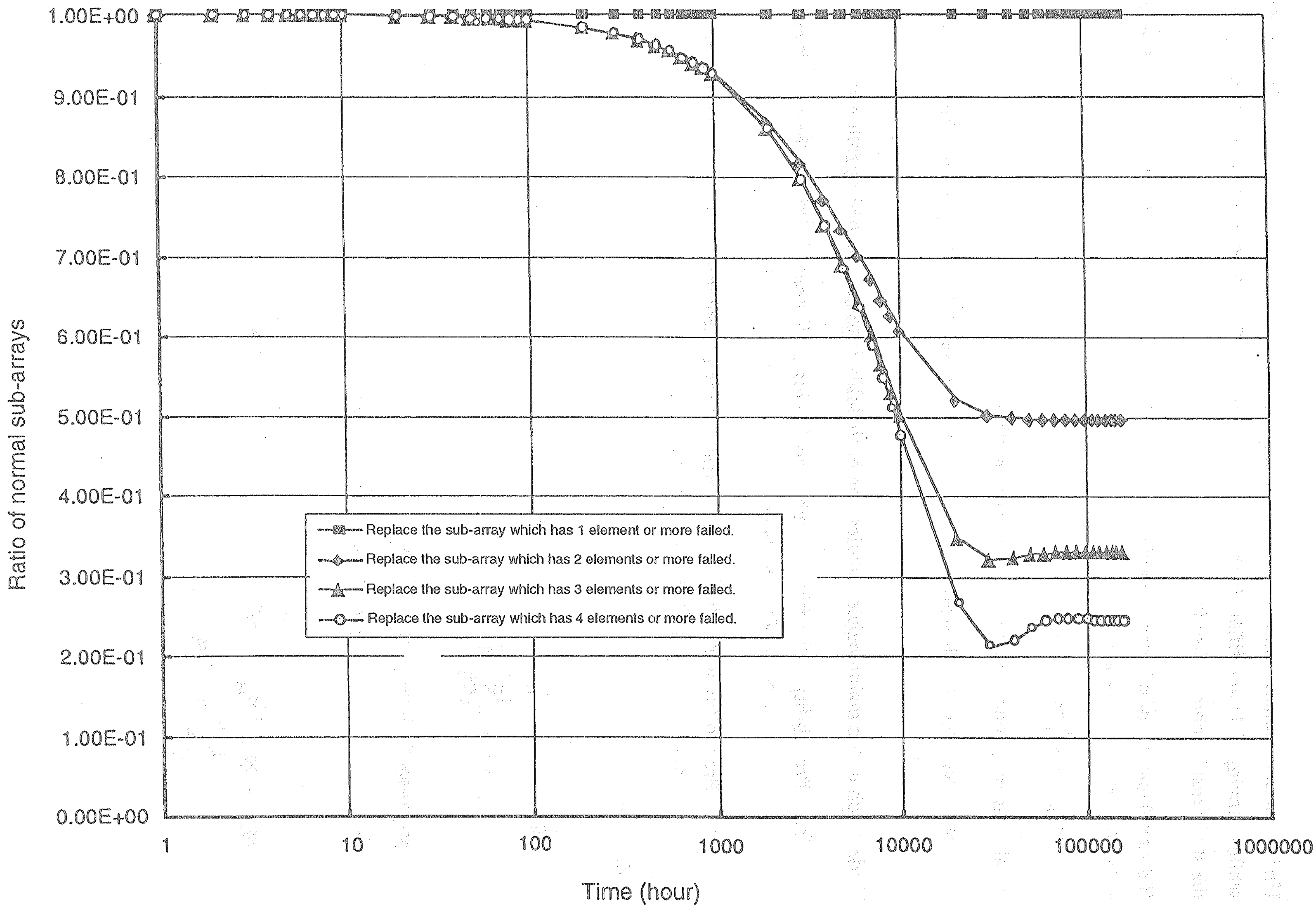


Fig. 7.2 Ratio of Sub-arrays Entirely Composed of Normal Elements

(5) Replace Sub-array which has i-Elements or More Failed (Policy i)

Under the maintenance policy of replacing any sub-array that may have i-amplifiers failed while allowing (i-1) amplifiers in the array to fail, we can find the formula given below from the study results obtained so far.

If the total number of sub-arrays required to avoid a decrease in output under Policy i is reckoned to be $N_{T(i)}$, then we can get:

$$N_{T(i)} = N \times \{76 / (76\text{-}i)\}$$

As already mentioned, moreover, it is assumed that:

N_k^n : Number of sub-arrays, each of which has k-amplifiers failed upon start of Time n (after completion of maintenance).

Under each of the maintenance policies, the probability is to be assumed as follows:

P_{qr} : Probability with which the sub-array having q-elements failed may have another r-elements failed after the lapse of a unit time $(q + r < i)$

: Probability with which the sub-array having q-elements failed may have another r-elements or more failed after the lapse of a unit time $(q + r = i)$

In this case,

$$N_0^n = NT(i) - N_1^n - N_2^n \cdots\cdots\cdots - N_{i-1}^n$$
$$= NT(i) - \sum_{k=1}^{i-1} N_k^n$$

$$N_1^n = N_0^{n-1} \cdot P_{01} + N_1^{n-1} \cdot P_{10}$$
$$N_2^n = N_0^{n-1} \cdot P_{02} + N_1^{n-1} \cdot P_{11} + N_2^{n-1} \cdot P_{20}$$

$$\vdots$$

$$N_{i-1}^n = N_0^{n-1} . P_{0(i-1)} + N_1^{n-1} . P_{1(i-2)} \cdots\cdots\cdots - N_{i-1}^{n-1} . P_{(i-1)0}$$
$$= \sum_{k=0}^{i-1} N_k^{n-1} . P_{k(i-j-1)} \qquad (7.5.1)$$

where

a) With q + p < i,

$$P_{qr} = {}_{76-q}C_r \, (1-\lambda)^{76-q} \cdot \lambda^r \tag{7.5.2}$$

b) With q + p = i,

$$P_{qr} = 1 - P_{q0} - P_{q1} - P_{q2} \cdots\cdots - P_{q(r-1)}$$
$$= 1 - \sum_{k=0}^{r-1} P_{qk} \tag{7.5.3}$$

From the above, we can get the probability in each case.

Sequentially calculating the gradually changing formulas will allow us to obtain the Number of Sub-arrays to be Replaced at Time n under Policy i ($N_d(i)$) as follows:

$$N_d(i) = N_0^{n-1} \cdot P_{0i} + N_1^{n-1} \cdot P_{1(i-1)} \cdots\cdots - N_{i-1}^{n-1} \cdot P_{(i-1)1}$$
$$= \sum_{k=0}^{i-1} N_j^{n-1} \cdot P_{j(i-j)} \tag{7.5.4}$$

Fig. 7.3 indicates $N_d(i)$ relative to i in each case after the lapse of 160 thousand hours. If the result has i = 42, it indicates the minimum value. It is difficult, however, to think that $N_d(i)$ has converged in relation to every i in 160 thousand hours. The calculation results already referred to indicate that the time to approach the convergent value according to an increase in i shows a tendency to increase. Convergence, therefore, may well be deemed to require a longer time.

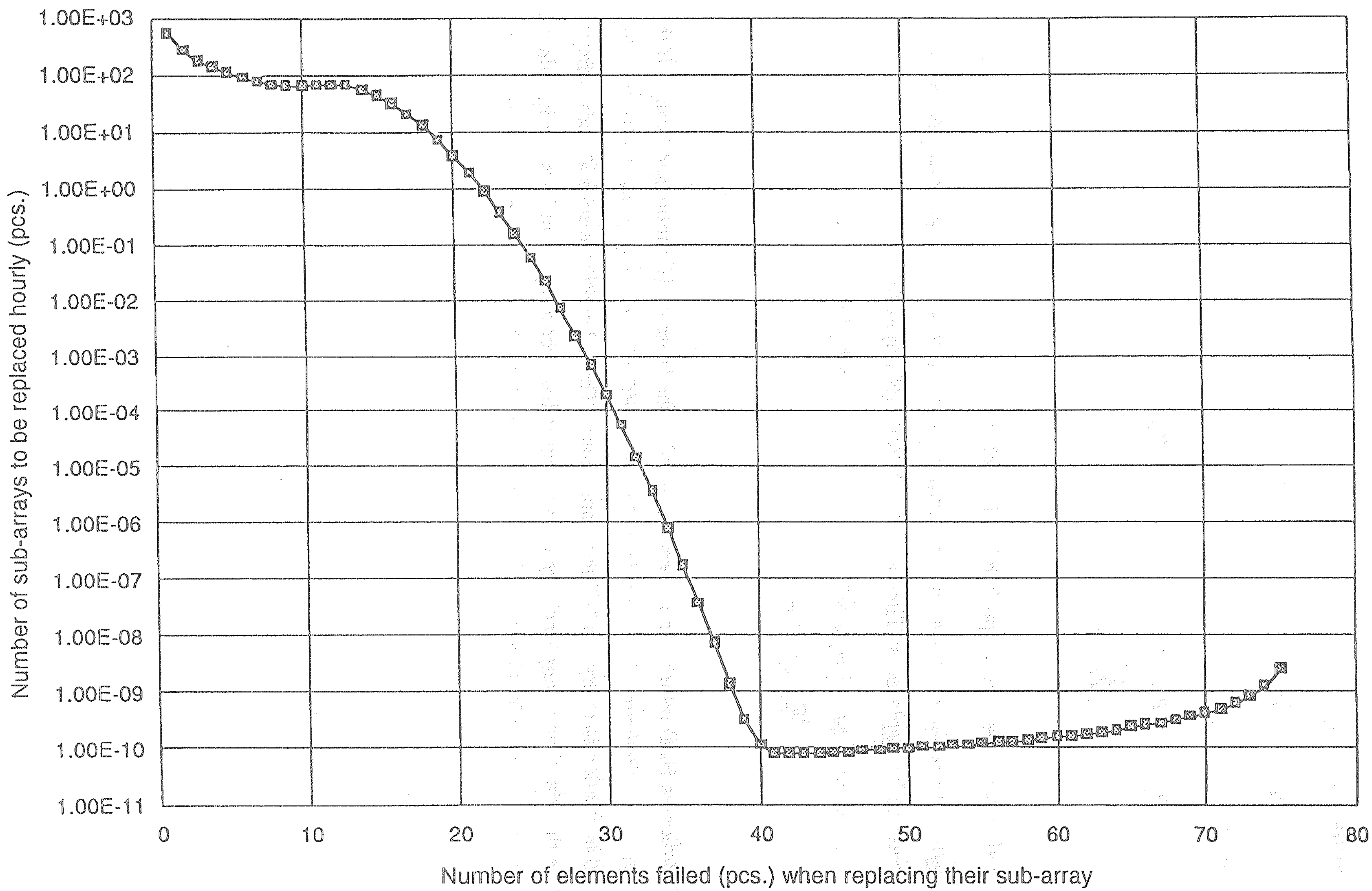


Fig. 7.3 Number of Sub-arrays Replaced under Each Maintenance Policy after Lapse of 160 thousand Hours

(6) Maintenance Policy

Now, assume that $N_{d(i)}$ has converged. Then, it may be considered that the number of sub-arrays in each failure mode becomes constant. Under a certain Policy i, in other words, we can get a formula to obtain the number of sub-arrays, each of which has a total of i - 1 elements failed, as follows:

$$N_1 = N_0P_{01} + N_1P_{10}$$

$$N_2 = N_0P_{02} + N_1P_{11} + N_2 P_{20}$$

$$N_3 = N_0P_{03} + N_1P_{12} + N_2 P_{21} + N_3P_{30}$$

$$N_{i-1} = \sum_{k=0}^{i-1} N_k \cdot P_{k(i-1-k)} \qquad (7.5.5)$$

Besides,

$$N_{t(i)} = N_0 + N_1 + \cdot\cdot\cdot + N_{i-1} \qquad (7.5.6)$$

In this case,

$$N_{T(i)} = N \times \{76/(76 - i)\}$$

and

$$P_{qr} = 76 - {}_qC_r\ (1 - \lambda)^{76-q\cdot\lambda r} \qquad (7.5.2)$$

where

$N = 6.6*E6$

$\lambda = 1000$ (FIT)

All from N_0, except N_{i-1}, are constant.

In other words, combining (7.5.5) with (7.5.6) will allow us to obtain i-th order linear simultaneous equations, which have i-unknown numbers from N_0 to N_{i-1}.

Under these simultaneous equations, obtain N_0 thru N_{i-1}.

$$N_d = N_0P_{0i} + N_1P_{1(i-1)} \cdot\cdot\cdot\cdot\cdot = N_{i-1}P_{(i-1)1}$$
$$= \sum_{k=0}^{i-1} N_k \cdot P_{k(i-k)}$$

Now, we can get N_d.

Table 7.1 shows Value N_d with i = 2 thru 75 as calculated under the policy referred to above.

Related curves are shown in Fig. 7.4.

Convergent Value N_d has shown a curve to take the minimum value, with i = 48. Coupled with an increase in i, the redundant system turns out to be effective so that the number of sub-arrays that need to be replaced decreases. Nevertheless, the redundant system will be larger to secure an output in the event of failure once i has exceeded a certain value. And the number of sub-arrays to be replaced will increase, accordingly.

Table 7.1 Calculation Results (Number of Sub-arrays Replaced Hourly)

i	Nd(i)	i	Nd(i)
2	255.8680	41	18.6676
3	171.7586	42	18.5272
4	129.7240	43	18.4087
5	104.5202	44	18.3210
6	87.7323	45	18.2369
7	75.7541	46	18.1837
8	66.7824	47	18.1527
9	59.8155	48	18.1444
10	54.2523	49	18.1596
11	49.7104	50	18.1992
12	45.9349	51	18.2645
13	42.7492	52	18.3572
14	40.0274	53	18.4790
15	37.6770	54	18.6326
16	35.6288	55	18.8208
17	33.8298	56	19.0472
18	32.2388	57	19.3162
19	30.8233	58	19.6333
20	29.5575	59	20.0052
21	28.4202	60	20.4404
22	27.3944	61	20.9494
23	26.4659	62	21.5460
24	25.6230	63	22.2478
25	24.8557	64	23.0783
26	24.1559	65	24.0690
27	23.5164	66	25.2637
28	22.9313	67	26.7248
29	22.3953	68	28.5447
30	21.9043	69	30.8661
31	21.4542	70	33.9231
32	21.0418	71	38.1293
33	20.6643	72	44.2947
34	20.3193	73	54.2678
35	20.0045	74	73.4552
36	19.7183	75	128.1459
37	19.4590		
38	19.2252		
39	19.0160		
40	18.8304		

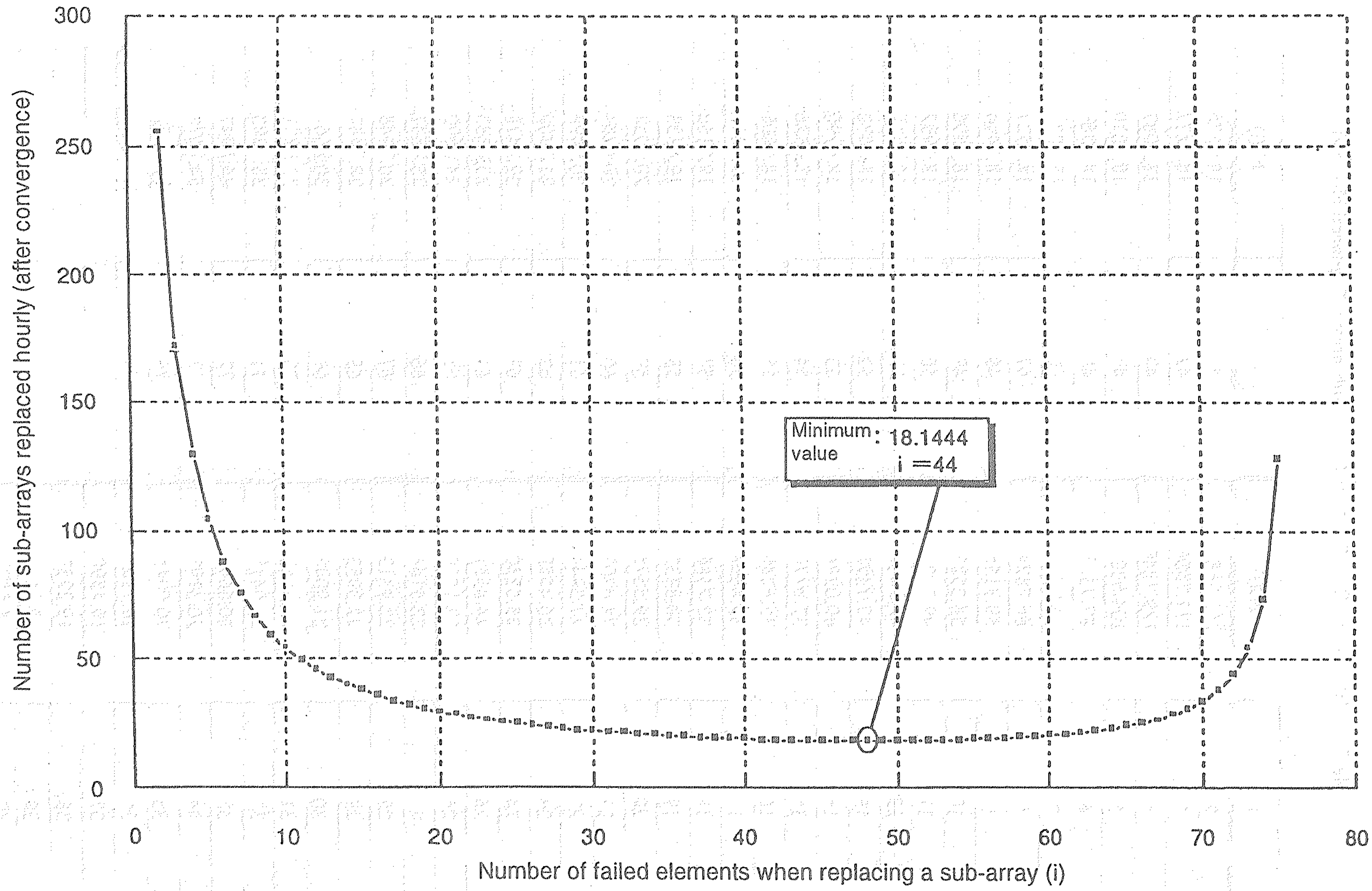


Fig. 7.4 Number of Sub-arrays Replaced Hourly (after convergence)

Based on the calculation results already mentioned, we may safely come to the conclusion that the maintenance policy to minimize the number of sub-arrays replaced hourly is:

"Once 48 of the 76 elements in a sub-array have failed, replace that sub-array."

The number of sub-arrays to be replaced, moreover, is 18.1 pieces per hour under normal operating conditions.

The reason why the wording "under normal operating conditions" is used here is because it is considered as the time when the number of sub-arrays to be replaced nearly reaches the maximum and that a considerable time (approximately one million hours = about 114 years according to an estimate) is required to reach the normal operating conditions.

The redundant number under the policy, moreover, will be as follows:

$$6.6E6 \times [\{76/(76\text{-}48)\}\text{-}1] = 6.6E6 \times 1.714$$

$$= 11.31E6$$

In other words, it is necessary to provide approximately 2.7 times the number of sub-arrays required without a redundant system. In those initial stages when hardly any elements fail, a significant quantity of electricity will be obtainable.

The optimum value referred to above, however, will be available when the only objective of minimizing maintenance is adopted. Essentially, therefore, it is desirable to minimize the cost having taken into account the cost involved in securing a redundant system.

Now, assume that:

Cost incurred on the replacement of one sub-array: C_1

Cost per piece of sub-array (parts and installation): C_s and

System service life (hours): T_1.

Then, we can get:

Replacement cost (C_m): $C_1 \cdot N_d(i) \cdot T_1$

Initial cost (C_i): $C_s \cdot 6.6E6 \cdot \{76/(76\text{-}i)\}$

i, therefore, should be obtained so that the sum of $C_m + C_i$ will be minimized.

At the present stage, each cost has not been clarified. i has been determined so as to minimize Cm, accordingly. Discussions hereinafter will proceeded with i = 48 as the optimum policy.

With this policy taken, a group of sub-arrays will have a size of approximately 16 kilometers in diameter on the moon.

From the viewpoint of ease of maintenance, the size of 16km in diameter is enormous, which should preferably be controlled after being divided into a certain number of areas.

Fig. 7.1 shows an example of the sub-array group divided into 36 equal control areas. In this case, each area covers approximately 5.58×10^6 (m^2), which may be converted to an equilateral square of approximately 2.36 kilometers per side.

In this case, the number of sub-arrays that need to be replaced in one control area may be averaged at:

18.1444/36 = 0.50 (pieces/hour)

This means that approximately one sub-array must be replaced every two hours.

To reduce the burden on one control area, furthermore, another concentric circle may well be added which is divided into 64 control areas, each of which covers $3.14 \times 10^6 m^2$ (an equilateral square of 1.77 kilometers per side). In this case, the number of sub-arrays that need to be replaced in one control area will be:

18.1444/64 = 0.28 (pcs./hour)

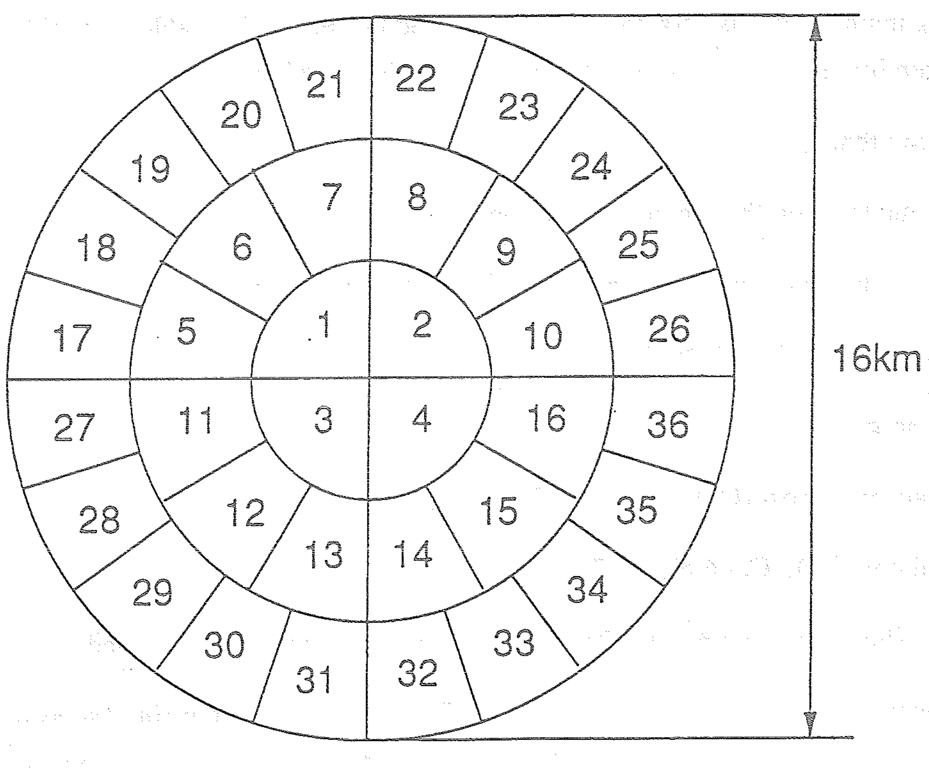


Fig. 7.1 Control Area Divided into 36

8. Studying a Decrease in Number of Parts

8.1 Configuration and Production Process of Microwave Monolithic IC (MMIC)

Fig. 8.1-1 shows a general IC production process (Reference 1). Fig. 8.1-2, moreover, is a sectional view of the MOSIC in each production process (Reference 1). In the wafer processing process, a mask pattern is printed optically to differentiate the portion to be treated from the one not to be. This printing is performed by thinly applying an ultraviolet ray curing resin and exposing it to ultraviolet rays by way of a mask so that uncured portions can be chemically removed (etched). In the stages where the process has ended, irregularities are mixed and aluminum electrode spattering is carried out. In this way, the wafer has unnecessary portions entirely removed together with the resin by the use of another chemical after being subjected to some kind of treatment. It then proceeds to the next process. In the assembly process, IC chips are packaged. The ICs for use on the earth are generally filled in epoxy resin and ceramic packages. The ICs for a microwave application have to be put in a metal housing, because of their characteristics.

Reference 1: LSI Process Engineering (Revised Ver. 2), Masatoshi UDAKA, Ohm-sha, 1988

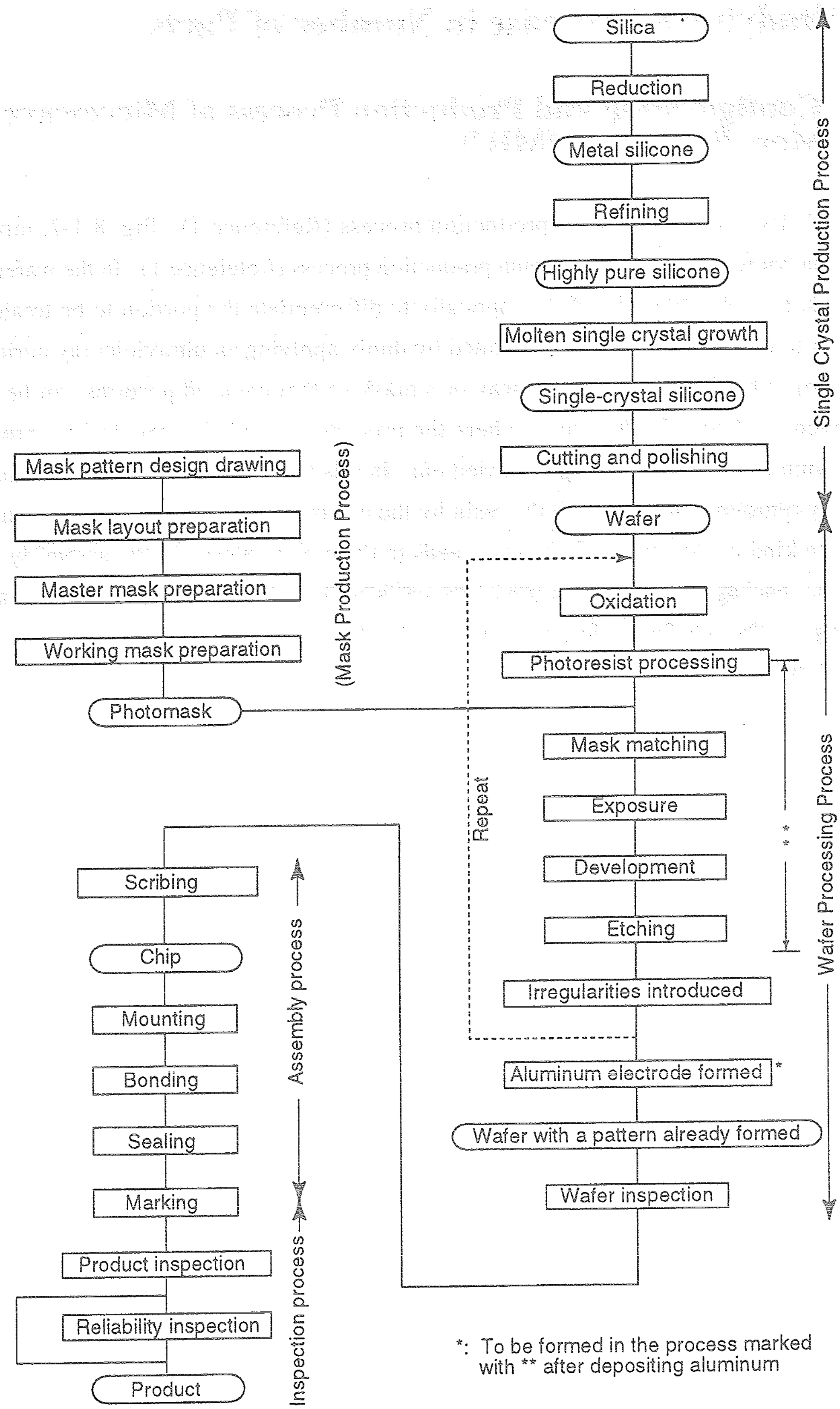


Fig. 8.1-1 IC Production Process

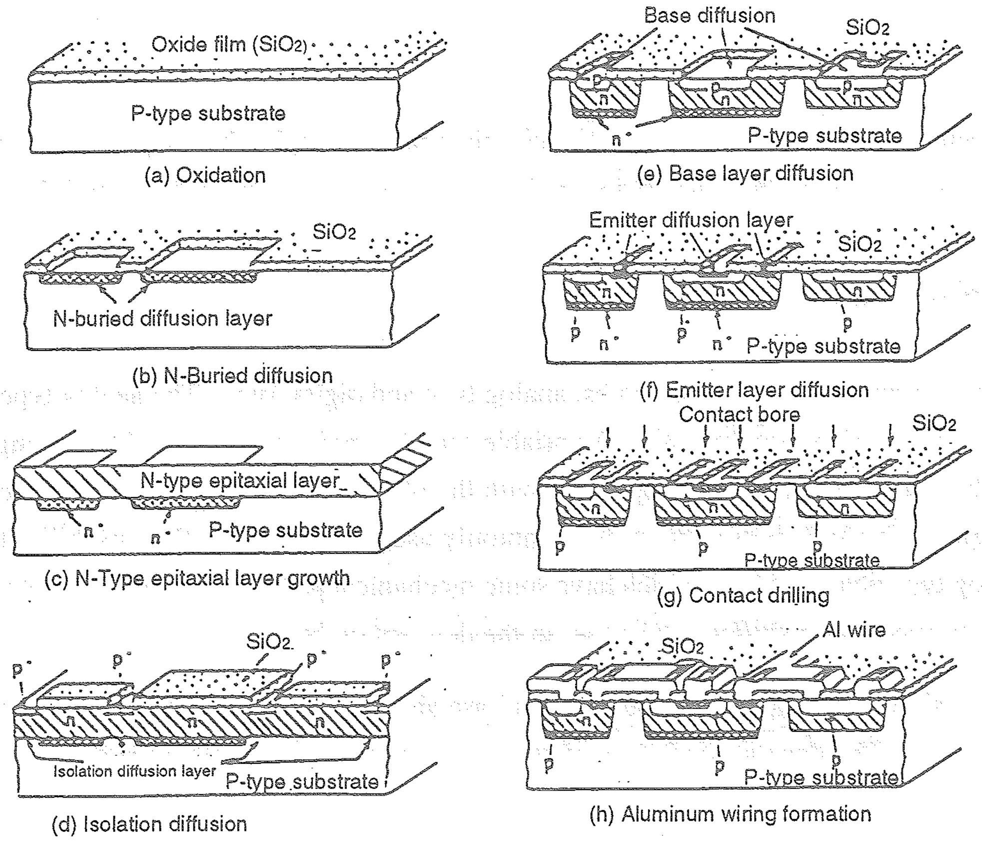


Fig. 8.1-2 Sectional Model in Simple MOSIC Production Process

8.2 Microwave Circuit Size

8.2.1 Microwave Circuit

To configure a microwave circuit as a flat circuit, a microstripping line is generally used. The lower the frequency on the microstripping line, the larger its circuit element will be.

8.2.2 Phase Shifter

Phase shifters are available in two types; analog type and digital type. The analog type permits the line length to vary continuously. A variable-length coaxial cable or the like belongs to this type. The digital type should be operated with the selection of a line with two or more fixed line lengths. This type is now the most commonly used. Considering their usability in space, the analog type phase shifters, which have some mechanical parts, are thought to be unsuitable. The digital type phase shifter is taken up in the description below.

Fig. 8.2-1 shows an example of the digital phase shifter employed on a microstripping line (Reference 2). The description below relates to typical digital type phase shifters.

(1) Switch Line Type Phase Shifter SLPS

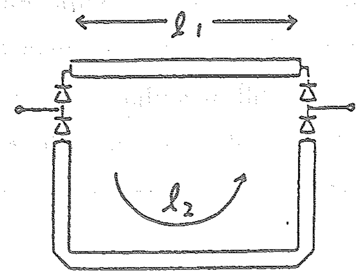
In this phase shifter, a difference in length between two strip lines selectable with a switch element is set so that an electric length equivalent to a shift requirement can be obtained. In reality, however, a phase error and a loss will take place due to the leakage through a line which is turned off. The line selector type phase shifter, therefore, is contrived to prevent such error and/or loss. The present system is unsuitable for the achievement of a high frequency and for many switch elements. Despite these disadvantages, however, the phase shifter has a relatively small insertion loss and a simple construction which allows for an easy design.

(2) Loaded Line Type Phase Shifter LLPS

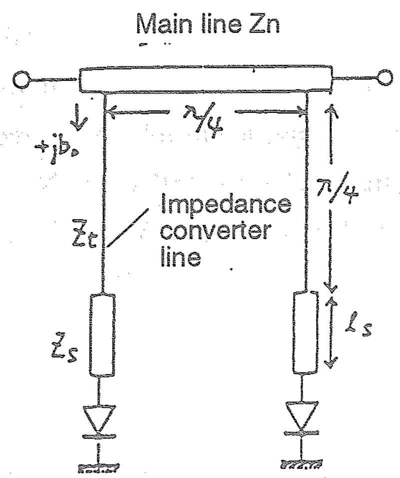
A phase shift is changed by selecting a loaded line, which has an identical magnitude of Susceptance b_0 connected in series with a main line of Standardized Impedance Z_m and Length $\lambda/4$, so that the code of that loaded line will be inverted. This circuit needs to have Target Phase Shift ϕ, Main Line Impedance Z_m and Load Susceptance b_0 which are related by the expressions below.

$$Z_m = \cos(\phi / 2)$$

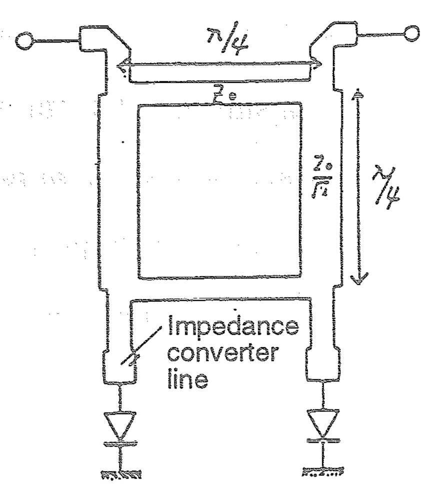
$$b_0 = \tan(\phi / 2)$$



(1) Switch line type phase shifter (SLPS)



(2) Loded line type phase shifter (LLPS)



(3) Branch line type (BLPS)

Fig. 8.2-1 Types of Digital Phase Shifters

A phase shifter of this type has a small insertion loss while allowing the phase to vary relatively little within the band (without being affected by the power transmission whose frequency is fixed). This method, however, does not allow a phase shifter to achieve a phase shift of almost 180 degrees. So, it is unsuitable for the phase shifter which may require a large phase shift. Besides, a loaded line type phase shifter is of complicated design. Nevertheless, it permits the number of switch elements to be reduced.

(3) Branch Line Type Phase Shifter BLPS

A phase shifter of this type selects a phase shift, based on a change in phase of Reflecting System Γ, which is caused by turning a switch element on and off. This method may not allow a required phase shift to be achieved by the switch itself with its phase shift stroke only. If so, an impedance converter circuit may be inserted to achieve the required phase shift. The method permits a significant phase shift to be achieved with ease. Nevertheless, it has a slightly large insertion loss while being of complicated design. A branch line type phase shifter, however, allows for a decrease in the number of switch elements.

(4) Comparison of Phase Shifters

Although there is a difference more or less according to the phase shift requirement, various types of phase shifters have their respective characteristics roughly related as described below.

Insertion Loss	: small SLPS < LLPS < BLPS large
Dimensional Construction	: small SLPS < LLPS < BLPS large
Frequency Characteristic	: low frequency SLPS, BLPS < LLPS high frequency
Phase Shift	: small phase shift SLPS, LLPS < BLPS
Number of Switch Elements	: large SLPS > LLPS = BLPS small

(5) Switch Element

As a switch element, a PIN diode is often used. More recently, however, there is an increasing number of FET-applied ones. The cost of an electronic scanning type antenna depends upon its switch elements. It is desirable, therefore, to reduce the number of switch elements employed as far as practicable. A smaller number of positive parts is also better, taking into consideration production on the moon. Shown below are the features of both PIN diode- and FET-applied switch elements.

(a) **PIN Diode**

The PIN diode, which has a small ON resistance (1 ohm or less), has a smaller insertion loss than an FET. From a configuration point of view, on the other hand, it is necessary to flow a bias current through an RF line so that a slightly complicated circuit will be employed. In addition, the PIN diode switch element has another disadvantage that its current consumption will become significant if a large number of diodes are employed. One diode has a current consumption of approximately 20 milliamperes. A current of 4 amperes or more is required for the 19-element antenna employing a 3-bit phase shifter.

(b) FET

A field effect transistor type switch element may be turned on and off with a voltage at the gate electrode independent of an RF line. As a result, its basic circuit is far simpler than that for the PIN diode. It has an ON resistance of approximately 2 ohms and eventually a large insertion loss. To make a phase shifter of MMICs, moreover, it is necessary to employ an FET.

Reference 2: Design and Analysis of Car-bone Antennas in a Mobile Satellite Communication Systems, and Challenges for the Future, Textbook, GIKEN Information Center, May 1991

8.3 SSPA Circuit Configuration

To achieve an output of 10 Watts at 2.45GHz, it is necessary to connect amplifiers in a number of stages in series. If the amplifier in each stage has Gain G_n, Total Gain G available in the amplifiers in series may be obtained by the following expression:

$$G = G_1 G_2 G_3 \ldots G_n$$

Currently, an SSPA has a gain of approximately 10dB per stage. It is necessary, therefore, to connect amplifiers in three stages in series. If the amplifier in each stage has a gain of 10dB, the total gain will reach 30dB. And an SSPA input power of 0.01W is required.

8.4 Studying MMIC Applicability

8.4.1 Phase Shifter Size

As gathered from Fig. 8.1-1, the size of a phase shifter is determined according to the working frequency. LLPS and BLPS, both based on $\lambda/4$, will have λ of approximately 12 centimeters at 2.45GHz, that is $\lambda/4 = 3$ centimeters. One BLPS, therefore, has a size of 3cm*3cm.

8.4.2 SSPA Size

Inductance and capacitance, working inside the circuit of an SSPA, are dependent upon the frequency. The SSPA operating at 2.45GHz, therefore, will be very large.

8.4.3 Production Process

As already mentioned, an IC production process is very complex, resorting to a large number of chemicals and production equipment. In addition, every process requires a very high level of cleanness. It is questionable, therefore, whether ICs can be produced on the existing surface of the moon.

8.4.4 Studying Applicability

As gathered from the study mentioned above, it is necessary to incorporate two or more FETs in a size of 3cm*3cm for a single stage of the phase shifter. To change the phase shifters in two or more stages over to an MMIC, it will be necessary to increase the size further. This size is far larger than the approximately 1cm*1cm generally available for an LSI.

In the case of an SSPA, it is likely that the circuit will have a large size if the amplifiers in three stages or so are changed over to an MMIC on account of a related circuit constant.

Generally, an IC is liable to be increasingly defective as the area gets larger. If such a circuit should be changed over to an MMIC, there will be a fear that the yield may decrease. Even when these ICs are produced on a production line on the earth, therefore, it is thought there will be a significant amount of defects.

Considering the production process problems on the moon, this would make it difficult to apply an MMIC to the power transmission system in the glass ocean.

8.5 Miscellaneous Measures

Another measure to reduce the number of parts for such a circuit without using an MMIC is to make it hybrid. In this case, however, it is fundamentally necessary to combine individual parts. Considering that the number of parts required will increase and that the production process will be complex, it is tought to be difficult to produce and assemble a hybrid circuit on the moon.

9. Studying the Cost

9.1 Prime Cost of Power Generated throughout Service Life by Power Source in Japan

According to the data available from the Ministry of International Trade and Industry, the cost of power generated throughout a service life by power sources in Japan is as shown in Table 9.1-1.

Table 9.1-1 Results of Estimating the Prime Costs of Power by Source (Based on the Operation Started up in Fiscal 1989)

	Construction cost (per kW)	Prime cost of power throughout service life (power transmission terminal) (per kWh)
Nuclear power	Approx. 310 thousand Japanese yen	Approx. 9 Japanese yen
Hydroelectric power in general	Approx. 640 thousand Japanese yen	Approx. 13 Japanese yen
Oil-fired thermoelectric	Approx. 190 thousand Japanese yen	Approx. 11 Japanese yen
Coal-fired thermoelectric	Approx. 230 thousand Japanese yen	Approx. 10 Japanese yen
LNG-fired thermoelectric	Approx. 200 thousand Japanese yen	Approx. 10 Japanese yen

(Source: "Nuclear Power Pocket Book" 1994 Edition, prepared under the supervision of Nuclear Power Bureau, Agency of Science and Technology, Japan Nuclear Power Industry Conference, P.13)

(Reference) Chart of the Grounds to Calculate the Cost of Power Generated in Fiscal 1989

Power Source	Hydroelectric, in general	Oil-fired	Coal-fired	LNG-fired	Nuclear
Output (kW)	10,000 ~ 40,000	600,000	600,000	600,000	1,100,000
Service year (year)	40	15	15	15	16
Fuel calorie	–	9,800kcal/l	6,200kcal/kg	13,000kcal/kg	–
Thermal efficiency	–	39.7%	39.1%	40.5%	–
In-house consumption ratio	0.4%	5%	8%	3%	4%
Number of employees per plant	3 persons	60 persons	70 persons	50 persons	100 persons
Labor cost per capita * (Japanese yen)	8,100,000	8,100,000	8,100,000	8,100,000	8,100,000
Ratio of fuel cost to prime cost of power	–	Approx. 60%	Approx. 40%	Approx. 50%	Approx. 20%

* Including retirement allowances, welfare expenses, etc.

** Approximately ten percent is spent to purchase condensed uranium.

9.2 Estimating the Prime Cost of Nuclear Power Generation

The prime cost estimation chart given in 9.1 does not show how to calculate the prime cost. To compare the prime cost with the requirement for the glass ocean system, a general cost calculation procedure is herein used to estimate the nuclear power prime cost throughout the service year, based on the values specified in 9.1.

The cost of power annually generated may be generally obtainable from the expression below.

Annual expenditure (yen)/annual supply power (kWh)

= prime cost of power generated (yen/kWh)

The term, annual expenditure, as used herein, relates to those expenses which will be incurred yearly to manage and maintain the equipment for a power plant constructed. It comprises such capital expenses as interest, depreciation expense, various taxes, etc. and such running costs as labor cost, repair/maintenance cost, fuel cost and so on. The majority of the annual expenditure is taken up by interest, depreciation expenses and fuel costs.

To calculate the annual expenditure, an annual expenditure ratio is predetermined. Except for fuel costs, a simple calculation method is generally employed to obtain the annual expenditure by the following expression:

Annual expenditure (yen) = construction cost (yen) × annual expenditure ratio

The annual expenditure ratio covers both annual expenses and running costs, such as interest, depreciation expenses, repair/maintenance costs, etc. except for fuel costs. Strictly speaking, its value varies from year to year. Adopting a different annual expenditure ratio from year to year, however, would make calculations complicated. A mean expenditure ratio, therefore, has been applied so that the amount of the current value for a certain period will be equivalent. Table 9.1-2 shows the annual mean expenditure ratios and service years by type of power plant.

Plant	Annual mean expenditure ratio (%)	Service year (years)
Hydroelectric Power Plant	12 ~14	Approx. 35
Thermoelectric Power Plant	15 ~19	Approx. 15
Nuclear Power Plant	18 ~20	Approx. 16

(Source: Electric Engineering Handbook, Society of Electricians, 1988, p.930)

The annual mean expenditure ratio is used to calculate the prime cost of the power generated in a nuclear power plant.

Calculations are based on the following prerequisites:

<Prerequisites>

Power plant capacity	: 4.4×10^6kW (1.1 million kW class $\times$ 4 plants)
Working ratio	: 70%
Service life	: 16 years

Ratio of fuel cost to prime cost of power generated: 20%

Unit construction cost	: 310,000 yen/kW
Annual mean expenditure ratio	: 19%

The construction cost may be calculated by the following expression:

$$\text{Construction cost (yen)} = \text{unit construction cost (yen/kW)} \times \text{power generated (kW)}$$
$$= 310{,}000 \text{ (yen/kW)} \times 4.4 \times 10^6 \text{ (kW)}$$
$$= 1.364 \times 10^{12} \text{ (yen)} = 1{,}364 \text{ (billion yen)}$$

The total power annually generated may be calculated by the following expression:

$$\text{Total power generated} = \text{power generated (kW)} \times \text{time (hours)} \times \text{working rate}$$
$$= 4.4 \times 10^6 \text{ (kW)} \times 8760\text{(h)} \times 0.7$$
$$= 2.7 \times 10^{10} \text{ (kWh)}$$

The annual total expenditure may be calculated by the following expression:

$$\text{Total expenditure} = \text{annual expenditure} + \text{fuel cost}$$
$$= \text{construction cost} \times \text{annual mean expenditure ratio} + \text{total expenditure} \times 0.2$$
$$= \text{construction cost} \times 0.19 + \text{total expenditure} \times 0.2$$

Therefore,

$$\text{Total expenditure} = (\text{construction cost} \times 0.19) / 0.8$$

$$= \{1.364 \times 10^{12} \text{ (yen)} \times 0.19\} / 0.8$$

$$= 3.24 \times 10^{11} \text{ (yen)}$$

The prime cost of power generated may be calculated by the following expression:

$$\text{Prime cost for power generated} = \text{total expenditure} / \text{total power generated}$$

$$= 3.24 \times 10^{11} \text{ (yen)} / 2.7 \times 10^{10} \text{ (kWh)}$$

$$= 12 \text{ (yen/kWh)}$$

9.3 An Estimate for the Glass Ocean

Based on the idea of estimating the prime cost for nuclear power generated as described in 9.2, the glass ocean construction cost is to be estimated to secure a power production cost at a level equivalent to that for nuclear power.

The glass ocean system is to have a power production capacity of 5GW.

If the system is composed of many sub-arrays, the working rate may increase remarkably. It is reckoned, therefore, to be 95%.

Since solar energy is to be utilized, the glass ocean system will be free from any fuel cost.

The system has a small number of operating parts. Unlike the earth, moreover, the moon does not have either air or water so that the system will not be adversely affected by corrosion or the like. As a result, the system may be deemed to have a far longer service life than that for equipment on the earth. As shown in Table 9.1-2, moreover, hydroelectric power plants have the longest service life among equipment on the earth. Consequently, they show a low annual mean expenditure ratio (12% thru 14%). The glass ocean system, on the other hand, is expected to achieve an annual mean expenditure ratio lower than that for a hydroelectric power plant.

Based on what has been discussed above, the prerequisites for the study have been established as follows:

<Prerequisites>

Power plant capacity : 5×10^6kW (1.1 million kW class × 4 plants)

Working ratio : 95%

Ratio of fuel cost to prime cost of power generated : 0%

Annual mean expenditure ratio : 10%

Prime cost of power generated : 12 yen/kWh

The total power annually generated may be calculated by the following expression:

$$\text{Total power generated} = \text{power generated (kw)} \times \text{time (hours)} \times \text{working rate}$$

$$= 5 \times 10^6 \text{ (kW)} \times 8760 \text{ (h)} \times 0.95$$

$$= 4.16 \times 10^{10} \text{ (kWh)}$$

The total expenditure may be calculated by the following expression:

$$\text{Total expenditure} = \text{prime cost of power generated} \times \text{total power generated}$$

$$= 12\ (\text{yen/kWh}) \times 4.16 \times 10^{10}\ (\text{kWh})$$

$$= 4.99 \times 10^{11}\ (\text{yen})$$

The construction cost may be calculated by the following expression:

$$\text{Construction cost} = (\text{total expenditure - fuel cost}) / \text{annual mean expenditure ratio}$$

$$= 4.99 \times 10^{11}\ (\text{yen}) / 0.1$$

$$= 4.99 \times 10^{12}\ (\text{yen})$$

The unit price of construction may be calculated by the following expression:

$$\text{Unit price of construction (yen/kW)} = \text{construction cost (yen) / power generated (Kw)}$$

$$= 4.99 \times 10^{12}\ (\text{yen}) / 5 \times 10^{6}\ (\text{kW})$$

$$= 998 \times 10^{3}\ (\text{yen})$$

$$= 998{,}000\ (\text{yen})$$

For nuclear power, the unit price of construction amounts to 310 thousand Japanese yen. For the glass ocean system to secure a power production cost nearly equivalent to that for nuclear power, therefore, it is necessary to limit the cost of equipping and constructing both glass ocean and earth systems to a level of approximately three times that for nuclear power.

9.4 Estimating Cost of Power Generated in SPS

Likewise, the prime cost of power generated in an SPS is to be estimated.

Calculations are based on the prerequisites described below. The annual mean expenditure ratio has been set equivalent to that for the glass ocean.

<Prerequisites>

Power plant capacity : 5×10^6kW

Working ratio : 98.4%

Service life : 30 years

Ratio of fuel cost to prime cost of power : 0%

Annual mean expenditure ratio : 10%

Unit haulage cost: US$12,500 per kilogram (1,250,000 yen/kg at an assumed exchange rate of 100 yen per US dollar)

The construction cost may be calculated by the following expression:

Construction cost (yen)

= SPS construction cost (except for haulage related cost) + haulage unit price × SPS weight

$= 2.67 \times 10^{12}$(yen) $+ 1.25 \times 10^6$(yen/kg) $\times 5.1 \times 10^7$ (kg)

$= 6.64 \times 10^{13}$ (yen)

The total power annually generated may be calculated by the following expression:

Total power generated = power generated (kw) × time (hours) × working rate

$= 5 \times 10^6$ (kW) $\times$ 8760 (h) $\times 0.98$

$= 4.29 \times 10^{10}$ (kWh)

The annual total expenditure may be calculated by the following expression:

$$\begin{aligned}\text{Total expenditure} &= \text{annual expenditure} + \text{fuel cost}\\ &= \text{construction cost} \times \text{annual mean expenditure ratio} + \text{total expenditure} \times 0.0\\ &= \text{construction cost} \times 0.10 + \text{total expenditure} \times 0.0\\ &= 6.64 \times 10^{13}\ (\text{yen}) \times 0.10\\ &= 6.64 \times 10^{12}\ (\text{yen})\end{aligned}$$

As mentioned above, the cost of power generated in an SPS may be estimated to be approximately 13 times that of nuclear power.

The SPS has a haulage cost taking up a significant percentage of the construction cost. If the haulage cost can be reduced in the future, it will be possible to reduce the cost of power generated in the SPS.

The glass ocean system also requires the cost of haulage to the moon. It differs from the SPS, however, in the sense that materials can be procured on the moon, too. How the haulage cost could be reduced and how the local procurement ratio might be increased may be considered as the key points in making the configuration of a glass ocean feasible.

The prerequisites mentioned above in relation to the SPS have been cited from the report submitted by Mitsubishi Research Institute, Inc. to NASDA in June, 1994 under the title of "A Survey of Space Infrastructure's Far-Reaching Effects."

10. Challenges for the Future and Conclusion

10.1 Subjects of Research into Microwave Power Transmission

The report presented herein is only an elementary proposal relating to wireless power transmission from the moon. For the proposed system to materialize, there are many subjects of research to be tackled in the future, such as technological development on earth, demonstration experiments in space, and so on. These subjects of research are summarized below. The underlined items are those which require space experiments.

(1) Developing element technologies for a power transmission antenna:

1. Frequency selection: 2.45GHz/5.8GHz/laser

   <u>Rainfall attenuation, and ionosphere passage characteristic</u>

2. Developing power transmission antenna elements, and developing antenna elements which match moon surface conditions and amplifiers.

3. Beam Scan Control Method

   <u>Phase shifter control</u> (phase shifter configuration method, phase determining method, and <u>power-incoming direction measurement method - interference meter</u>), and <u>retrodirective antenna system</u>, (<u>pilot signal frequency</u>, receiving antenna, circuit configuration, and <u>ionosphere influence</u>)

   Control from incoming power distribution

   Sub-array dimensions

4. Aperture plane distribution (radiation pattern), Gaussian distribution, Taylor's distribution, grating lobe and side lobe

5. <u>Feasibility of Extremely Large Antenna</u>

   Functioning as Active Phased Array Antenna

(2) Developing a Microwave Circuit

1. Increasing the output of silicone semiconductor amplifiers
2. Increasing the efficiency of silicone semiconductor amplifier
3. Countermeasures to suppress higher harmonics
4. Temperature regulation, 60 degrees centigrade or below
5. Feasibility of production on the moon, merits of microgravity
6. Application to mass production, MMIC and adjustment omission (gain and phase)

(3) Developing a Power-receiving Antenna

1. Improving microwave-DC conversion, circuit configuration, and receiving antenna
2. Developing a rectifier element, high voltage-resistant diode and/or electron tube
3. Reception direction control, and the relative positional relationship between moon and earth

(4) Developing Power Generator Systems

1. How to connect the power generator with an amplifier:

   Stabilizing the power supply, ON/OFF control (radiation pattern), and integration

(5) Evaluating the Microwave Propagation Characteristic

1. Evaluating the effects on the ionosphere, plasma heating and exciting plasmatic waves
2. Evaluating the effects on the atmosphere

(6) Evaluating Effects on the Environment

1. Evaluating effects on the electromagnetic environment, communication and electronic equipment
2. Evaluating effects on living things

10.2 Demonstrative Experiments in Space

For the proposed system to materialize, it is considered absolutely necessary to evaluate the performance of the above-mentioned research subjects through power transmission experiments, with the following stages taken into account:

(1) Ground Power Transmission Experiment

Some experiments to transmit power between fixed points or to a flying object (airship, helicopter or aircraft) are to be conducted to measure the basic characteristics of a developed microwave power-transmitting/receiving system and to evaluate its performance.

(2) Low-orbit Satellite Experiment (satellite group and rocket experiment)

This is an experiment to evaluate developed technologies in space. At the same time, it is aimed at testing those items which cannot not be confirmed in any other than a space environment (underlined).

1) Remote Phase Control Performance Test

   (Testing the performance of controlling microwave beams, using a pilot signal from the earth)

2) Measuring the microwave ionosphere passage characteristics
3) Measuring the microwave atmosphere passage characteristics
4) Microwave/ionospheric plasma interaction experiment
5) Evaluating the effects on communications

(3) Lunar Surface Experiments

Several power transmission antennas are to be located on the moon to test the phase control and environment on the moon, thereby evaluating and demonstrating the technologies required for microwave power transmission.

10.3 Conclusion

Not such a long time has passed since substantial research into microwave power transmission was begun. And only a power transmission test at a maximum of one kilometer has been conducted so far (Goldstone). There are a lot of further subjects to be researched from now on. Microwave power transmission, however, involves no problem, in principle. And the existing research challenges, moreover, are fully feasible at the technological level available today. For wireless power transmission from the moon to materialize, it is considered important to proceed step by step while repeating developments and demonstrative experiments. Microwave power transmission, moreover, has a lot of applications not only in full-scale space power transmission but also on the earth, such as the transmission of power to microactuators, conduit robots, wireless relay platforms in the stratosphere and isolated isles. Upgrading the technological level of microwave power transmission while making these applications materialize is considered the way to bring about wireless power transmission from the moon.

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