# Development of Spray Robot for Fireproof Cover Work

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## §1. INTRODUCTION

The robotization in industry has actively been progressing in Japan. This has been growing impact onto the construction field as well.

The labor productivity in the construction field has not been increased for a decade and robots have been expected to increase productivity. We have been studying application of robotics to construction. The spray robot system developed by us is the results from such a need.

Fireproofing cover material for steel are required to keep strength of steel structure during fire. One process of fireproofing is to use a solid board, the other is to spray fireproofing materials. Three spraying processes are used and they are dry, wet and semi-dry. The semi-dry process is the most popular one due to economical reason.

The spraying of fireproofing material is carried out by construction workers on site. Rolling tower for scaffolding is used. The worker on the scaffolding have to wave the spray nozzle. The working environment, however, is quite bad with small particles of rock wool filling surrounding area. As fireproofing has a detrimental effect on working environment and involves the repetition of spray motion, it is a job well suitable for a robot.

The purpose of this spray robot is to relieve workers from poor conditions and to increase the processing speed.

## §2. OUT LINE OF SHIMIZU SITE ROBOT-1 (SSR-1)

Initial motivation for developing SSR-1 comes from a demand of the construction site which has many problems about work condition control of fireproofing cover work. Managers and foremen on site have wanted to improve the spray work conditions better than before. Then, 1982, Research Institute and Construction Machinery Division of Shimizu Construction Co., Ltd. organized the task force for the development of a spray robot system. This task for force's activity consisted two stages, the first is to design a robot system and to manufacture the machine, the second is to apply the robot system to a actual spray work and to obtain various kind of information and data about work conditions, quality of the robot's spraywork, and machines.

The task force of the developing SSR-1 established three purposes;
1) To relieve the human worker from the environment with high dust concentration.
2) To decrease a number of workers to improve the labor productivity.
3) To speed up the spray work to shorter the priod of fireproofing cover works.

The purposes had to be accomplished under the condition that the quality of spray work by robot was almost the same as was done by human workers.

### 2.1 Conditions for system design

The spray work on site is one of the typical human works which require technics and skills and such works are difficult to be automatized by conventional machines for construction. Then the task force began to design the spray system with a spray robot for a manufacturing industry. And it established the design conditions as follows;
1) The same materials and machines for material supply should be used.

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2) The robot must have mobility.
3) The robot should work sequentially and continuously without human help.
4) The robot should be capable of travelling and positioning on the dusty and dirty floor.
5) The weight of the robot should be within the limit of design load (300 kgf/m$^2$).
6) The size of the robot should be determined according to a size of the lift cage to be set up on site.
7) The robot must have safety functions for human workers, finished building (floor, girders and beams, pillars, curtain walls, glasses, and so on), and the robot itself.

The task team has chosen the system among several alternatives.

In Japan, manufacturers are providing many types of playback robots. KTR-3000F (KOBELCO-TRALLFA SPRAY ROBOT) was introduced because the specifications listed below are satisfied.

1) To have large quantity of the menory device to be able to memorize many spray patterns.
2) To be able to carry the nozzle for spray more than $2 \sim 3$ kgf (5 kgf enough).
3) To be able to use the continuous pass (CP) control for teaching the robot.

## 2.2 System structure of the spray system using SSR-1

The spray system has material supplying plant and SSR-1 for spray works.

### Material supply

Materials for fireproofing (semi-dry type) are rock wool and cement milk. Rock wool which is poured into the feeder is carried upward on the air flow created by the blower. The air with rock wool goes into the wool agitator through the flexible hose (3 inch dia.). The flow with rock wool is stabilized when air goes through the wool agitator.

Cement milk is prepared in the cement mixer. The weight ratio of the water and cement is about 2:1. The cement milk is pumped up through 1/4 inch flexible hose.

The material supplying plant is located on the 1st floor or on the basement, less than about 100m below the spray works. (Fig.1)

### Manipulator

The manipulator can be put in action programs directly by manual.

The spray robot consists of four main components: base, vertical arm, horizontal arm and wrist. This manupulator has 6 freedoms driven by the playback control system consisting of electro-hydraulic servo control.

The hight and width of the moving area is about 2m x 3m. Because of the flwxible wrist type, teaching works are not difficult in this moving area. Control wires, hydraulic hoses and material hoses are mounted on the supporters which are set every 1m interval. As these supporters can move smoothly on the floor, hoses and cables are protected from wearing out.

**Traveller**

The manipulator is mounted on the traveller which is made of an alloy of aluminium with higher strength than normal aluminium. Then the traveller's weight is 220kgf.

The traveller has 4 outriggers with wheels and the robot can stand vertically when travelling.

**Control Equipment**

The manipulator has a control equipment for itself, and the traveller has a sequential controller which controlls the traveller and the manipulator.

The manipulator control equipment (CRC system = Computer Robot Control) has CP/PTP teaching and CP play back control functions. CRC controller consists of one pair of floopy disc drive unit and other computer circuits. CRC system allows 64 programs and the maximum programming capacity is 128 minuts.

Connecting the CRC system with the sequential controller, SSR-1 can playback and repeat the many kinds of programs. The total possible working time is lower than 2 hours.

The traveller control equipment has also the oscillator for the tractor guiding and steering.

**Tractor**

The tractor is driven by electric power of batteries (DC 24V charging every 8 hours) and guided by the path wire which is connected to the electromagnetic induction oscillator (3.5kHz). For the sensing of the magnetic field of the path wire, one pair of the coil is attached to the front axle. One magnetic switch that can recognize a iron plate (80 x 80 x 1t) is also attached to the front axle and for the sensing of the stopping point of the tractor.

This tractor can be operated by manual and antomatic, changing the mode switch on the tractor or on the controller.

## §3. SPRAYING RESULTS AND PROBLEMS OF SSR-1

### 3.1 Outline of the spraying work

SSR-1 was applied on The 43rd Mori Building. This building is suitable for SSR-1 because the beam distances are all 3.1 meters per module. The chart of the spray work is shown in Fig. 4.

The travelling path of SSR-1 is shown in Fig.5. The curve path was determined by trial and error.

We programmed chart of the spray work on the controller which can control travelling, stopping and spraying.

### 3.2 Results of the application (SSR-1)

#### 3.2.1 Work conditions

We measured the dust concentration as an index for working conditions. A digital dust meter and a low volume air sampler were used for the measurements.

The conventional coefficient of the mass concentration K ($mg/m^3$) is determined by the digital dust meter and the optical disperse concentration C (CPM; Count Per Minute). Then we calculate the mass concentration M ($mg/m^3$).

$$M = K \cdot C$$

Fig.6 shows the results of dust measurements. The dust concentration depends on the distance from the nozzle.

#### 3.2.2 Work Efficiency

We evaluated the work efficiency by checking spray time per determined area. As a result of this evaluation, it was found that the processing speed was almost twice as fast as the conventional method.

Fig.7 shows a pareto diagram for preparing robot system. There are some new tasks involved. The placement of a wire path and a plate for stopping points and the lifting work of the robot system are not included in the conventional method.

#### 3.2.3 Quality

The fireproofing ability is determined by the specific gravity of rock wool and the thickness of the materials. The specific gravity of rock wool must be greater than 0.3 and the thickness of the fireproofing required is determined.

We found the specific gravity of rock wool sprayed by the robot is almost similar to the one achieved by a human worker. The major points for discussion concerning the dispersion of the fireproofing are shown in Fig.8. The biggest problem is to uniformly supply the material for spraying.

## §4. OUTLINE OF SSR-2

Following the SSR-1, the SSR-2 was developed to improve some functions of the SSR-1 on jobsite. Main items for improvement are;

1) To introduce a new positioning system in relation to a beams to be sprayed.
2) To travel and gyrate by the robot itself.
3) The path wire for guiding the robot should be eliminated.
4) To improve the feeder to be able to supply rock wool more uniformly.

Fig.9 shows the structure of the SSR-2.

The specification of SSR-2 are shown in Table 2.
The main items improved are shown in Table 3.
The outward figure is shown in Fig.10 and Photo 4.

## 4.1 Main components of SSR-2

### (1) Manipulator

Fundamentally, the manipulator is similar to the SSR-1's, but to make the teaching task easier, the serbo cylinders of the manipulator were replaced by the light friction type cylinder. The sensor for measuring distances was attached to the end of the robot arm.

### (2) Travelling Device

The travelling device for the SSR-2 was designed to be able to gyrate at the same area.

The travelling device consists of the stand frame with 4 outriggers and the traveller frame with 4 wheels. The stand frame has 4 outriggers, hydroulic control valves, joint box for electric wires, sensors for collision avoiding and spacers for changing the height of the manipulator. The traveller frame has the gyrating and travelling drive units, and the sensor (rotary encoder) for measuring distances to be travelled. These 2 frames are connected at the center of the each frame. These 2 frames enable the traveller to act as to go strait, stop, stand by 4 outriggers, gyrate $0 \sim 90^{\circ}$ right (or left), and so on.

### (3) Control Device

The control device of the SSR-2 is composed of the manipulator controller and the travelling device controller.

The manipulator controller is as the same as the SSR-1's.

The travelling device controller is designed to control the travelling sequence and to calculate the travelling position data (distance, height, angle).

These data are calculated by the 16 bit-computer control system (TM9995, 16KB ROM, 14KB RAM). In order to set the traveller at the initial position with good precision, the additional pendant box for manual was attached to the traveller's controller.

### (4) Device for supplying materials

We improved the device for supplying rock wool which influences the dispersion of the thickness of the fireproofing. The hopper of the rock wool feeder was attached to the additional stirring shuttlecock and the vibrator.

## 4.2 Positioning method of the traveller

The positioning method of the traveller is the main character of the SSR-2. The path wire was used for the SSR-1, however, the SSR-2 no longer need to follow any path wires.

The SSR-2 is able to travel by itself with the sensor for travelling distance. Even the SSR-2 travels under program controls, slight deviation caused by the uneven surface of the floor. The Fig.11 shows the method of adjusting positions of the traveller.

The sensing device to confirm the positions, attached to the end of the manipurator's arm, consist of the potentiometer and the rod. The SSR-2 measures its position by pushing the rod against the web (2 points) and flange (1 point) of the beam. It memorizes the basic value of pushing strokes $e_0$ (100 mm). The distance of the two pushing points of the web are 2,000 mm. After travelling, the SSR-2 pushes the beam for measuring and memorizes the value of the $e_1$. $e_2$.

The difference of value Q (degrees of rotation) and L (distance between the robot and the beam) (Fig.11) are calculated approximately as following,

$$Q = \arctan \frac{e_1 - e_2}{2000}$$

$$L = e_0 - \frac{e_1 - e_2}{2}$$

These values are calculated by the computer, and then the SSR-2 adjusts its position. Fig.12 shows the sequence of adjusting.

## §5. RESULTS OF THE APPLICATION (SSR-2)

The SSR-2 was applied to the TOSHIBA Building project.

This building has 40 stories having the floor plan and the steel frame design with standardized. The SSR-2 sprayed about 1500 m$^2$ on 35th and 36th floors' girders and beams. Fig.14 shows the travelling patterns for spraying by the SSR-2.

### 5.1 Results of the spraying work

#### Work efficiency

From the view point of economy, the comparison of the work efficiency between the robot and human is important. Fig.18 shows the relation of a human workers' efficiency and the SSR-2.

The SSR-2 can spray faster than a human worker. But SSR-2 needs the time for teaching and transporting.

In Fig.17 the time measuring unit is introduced. One time measuring unit is a period for spray works from (1) to (3) shown in Fig.14 and the content of one unit is shown in Fig.15.

The SSR-2 takes about 22 minutes for one unit and a human worker takes about 51 minutes. Therefore the SSR-2 can spray two times faster than a human worker.

Time measuring unit does not include a finishing and pressing the surface of fireproof and cleaning works by workers.

Additional to the characteristic such as higher efficiency, the SSR-2 does not need much man power for the preparation of the spray work. Fig.16 shows the preparation man power needed of the SSR-2. 11.5 man-day needed for the SSR-1 preparation, but for the SSR-2 only 2.08.

This shortening of the preparation time contributes to the improvement of the efficiency of the robot system.

### 5.2 Quality of the spray work

According to the improvement of the stopping point precision and the rock wool feeder, the dispersion of the sprayed thickness decreased and become almost equal to the one by a human worker's. Fig.18 shows the result of the thickness measured before finishing works.

## §6. CONCLUSION

The SSR-1 and SSR-2 have accomplished the initial purposes of the development of the spray robot system. But, they have not fully been developed yet. We can find many items to be further improved. Some of the example are;

1) To make the robot operation system much easier
2) To train robot operators
3) To increase the capacity of the material feeder and the speed of the robot's playback actions
4) To change the teaching method from directly to remot operation using CP control or numerical control

Recently, some people have too much expectation on the robot and robotics. But, it is almost impossible to build up suddenly a human-less construction system with the highest technologies.

We have to continue the research and development of robots step by step, intending to eliminate unsafe works and improve the productivity of construction. It is true that robotics is a very powerful tool for the improvement of the construction works. Therefore engineers of the construction field should be familiar with robotics.

I conclude that, at this present stage, a good construction robot can not be produced unless a lot of problems for site application overcome.

Finally, I appreciate all the advises given by engineers and experts of construction sites and KOBELCO.

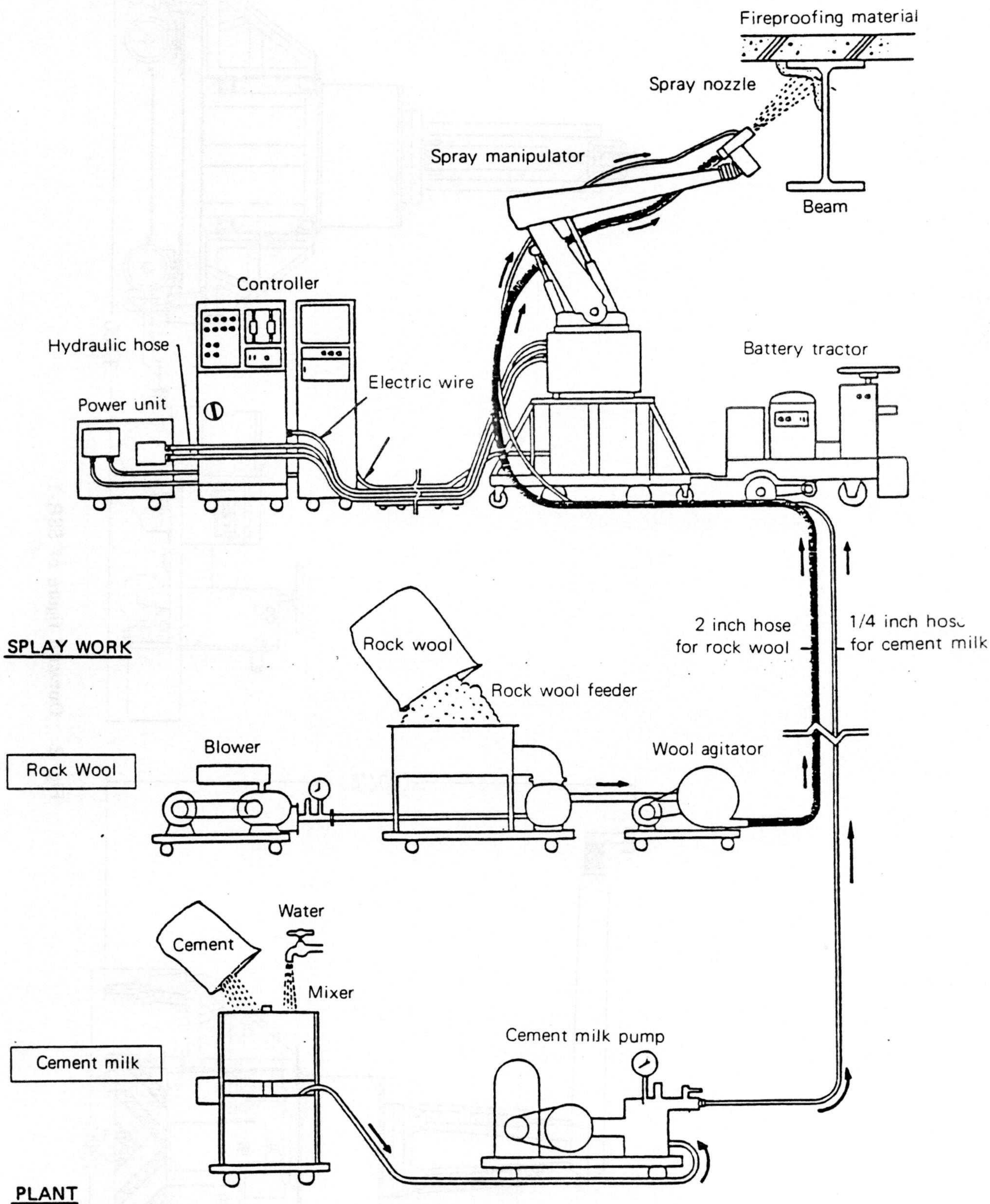



**Fig. 1 Rock wool spray system with SSR-1**

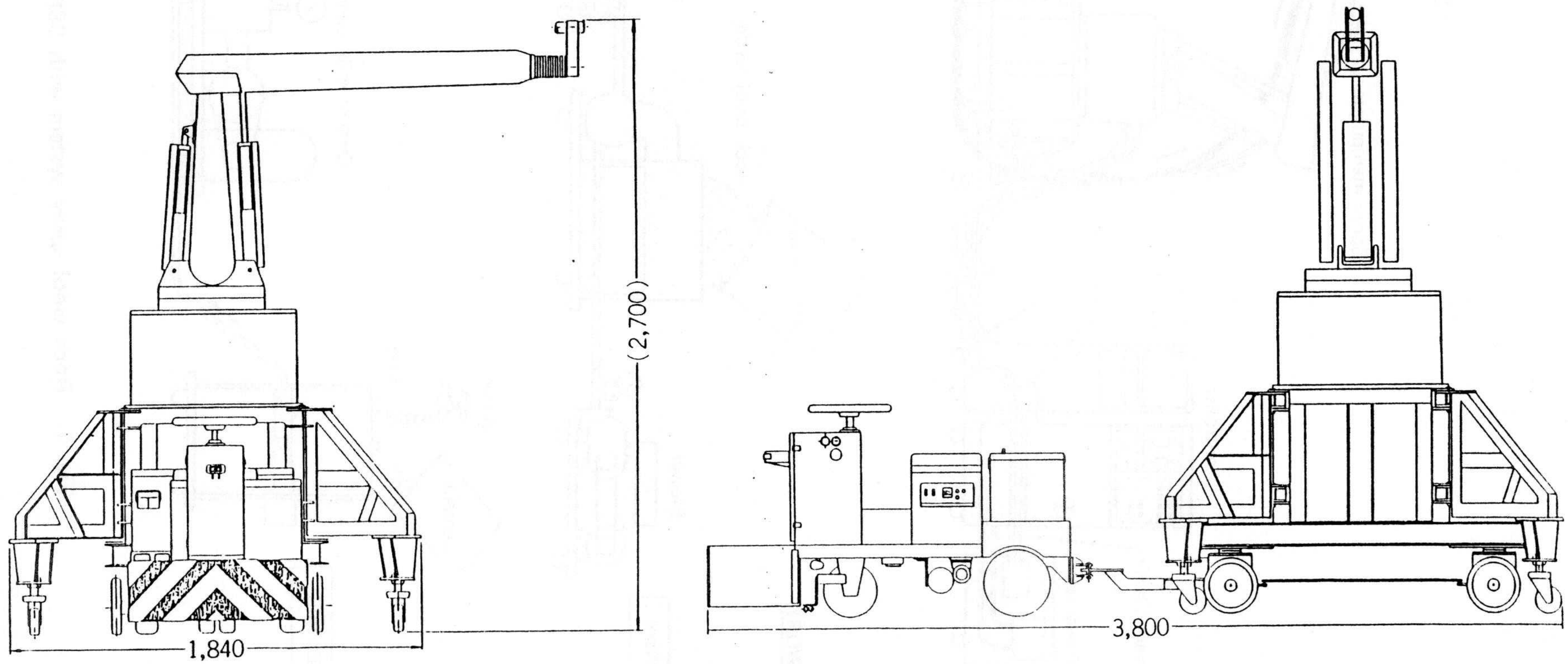
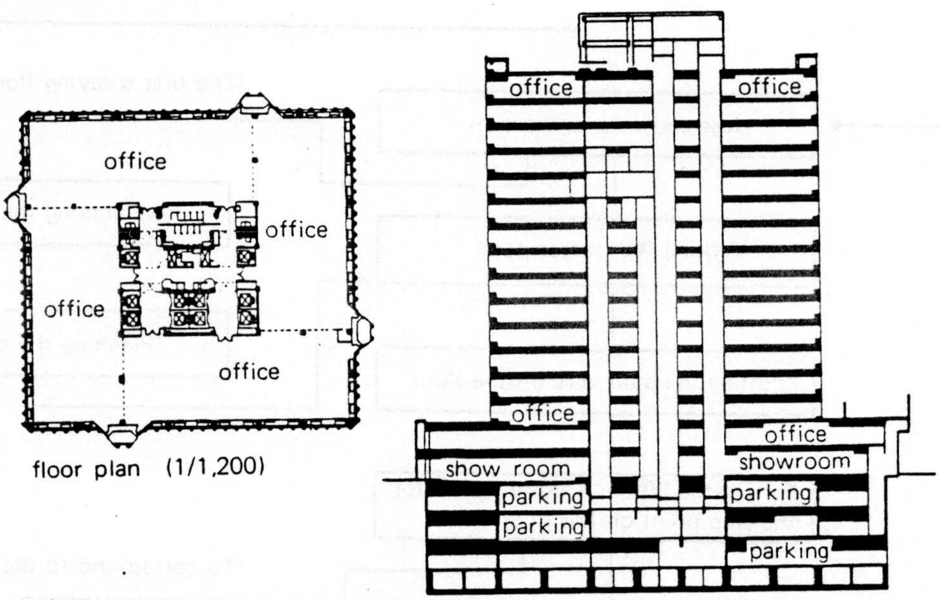



**Fig. 2 Outward figure of SSR-1**




floor plan (1/1,200)

section (1/1,200)

**Fig. 3 Outline of Mori Building No.43**

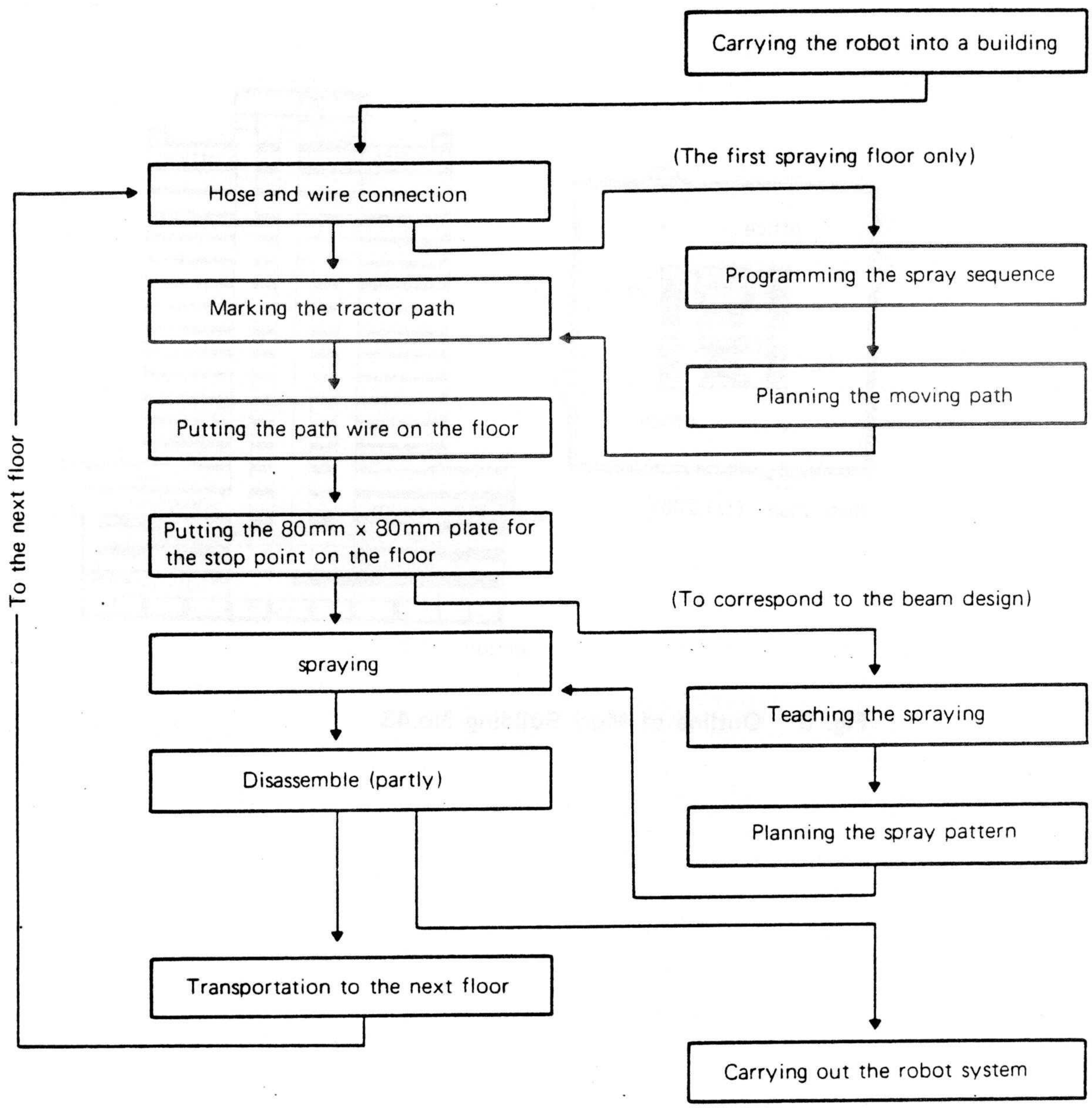



**Fig. 4 Flow diagram of the SSR-1**

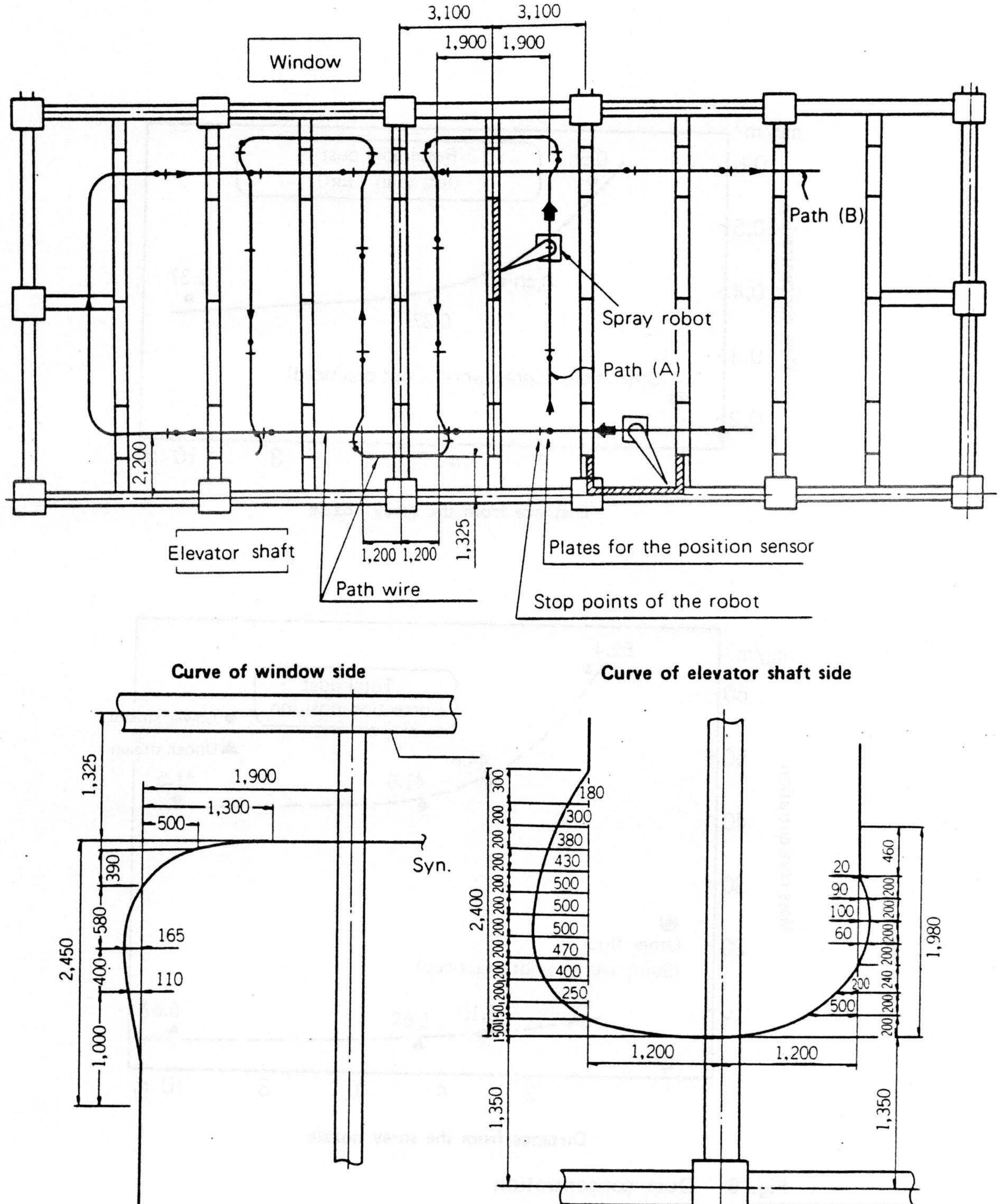



**Fig. 5 Planning of the path wire**

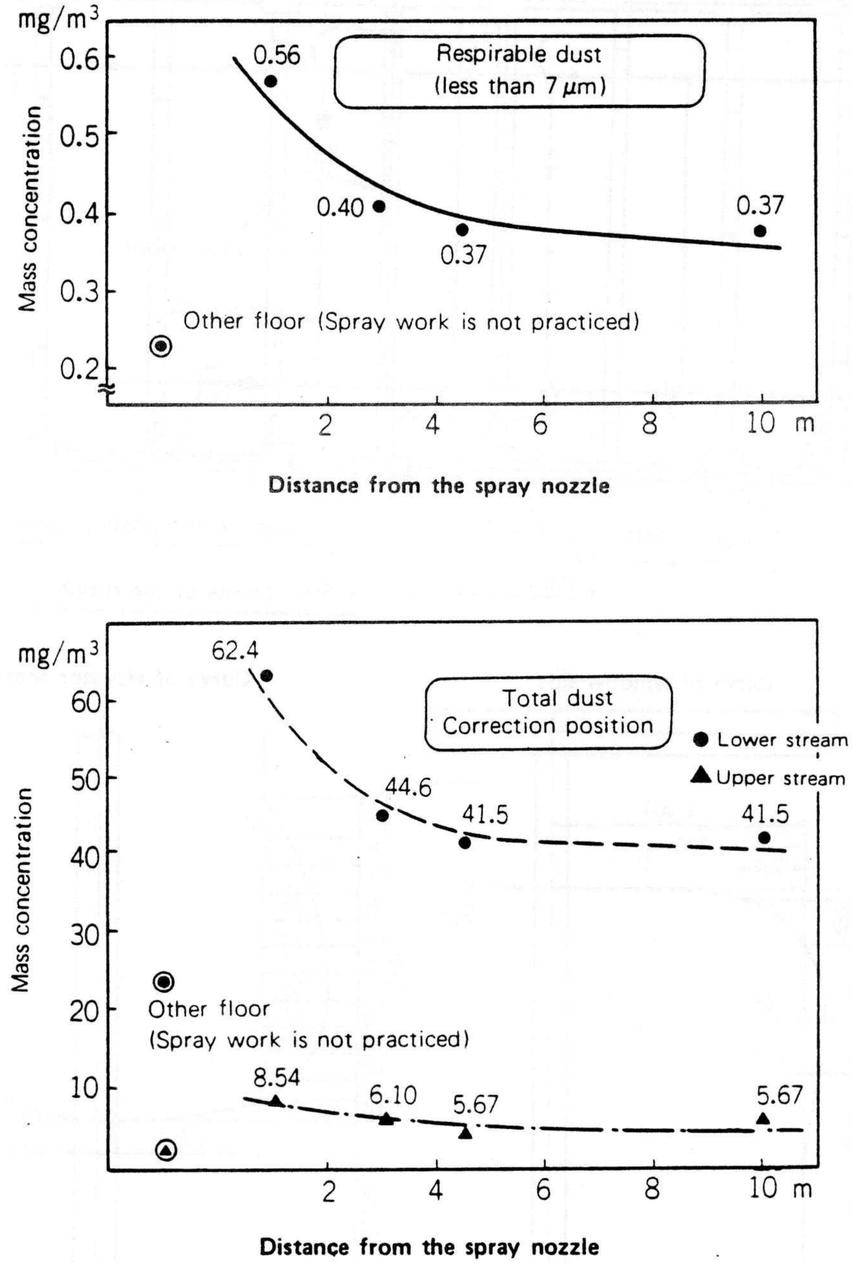



**Fig. 6 Dust concentration**

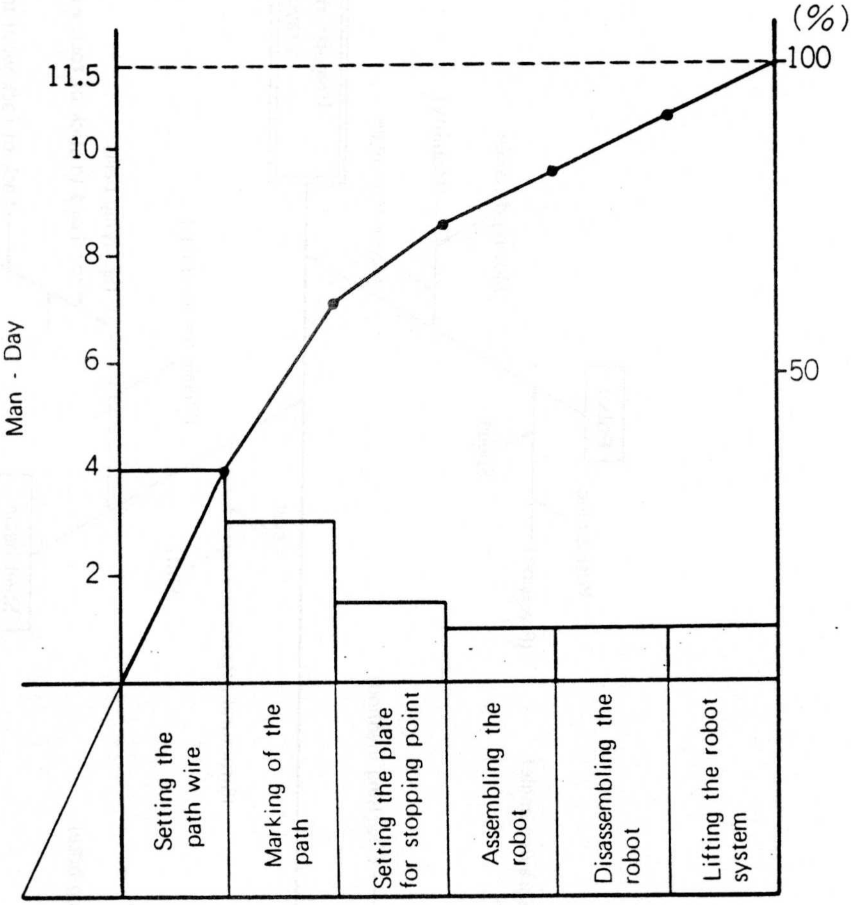



**Fig. 7 Manpower**

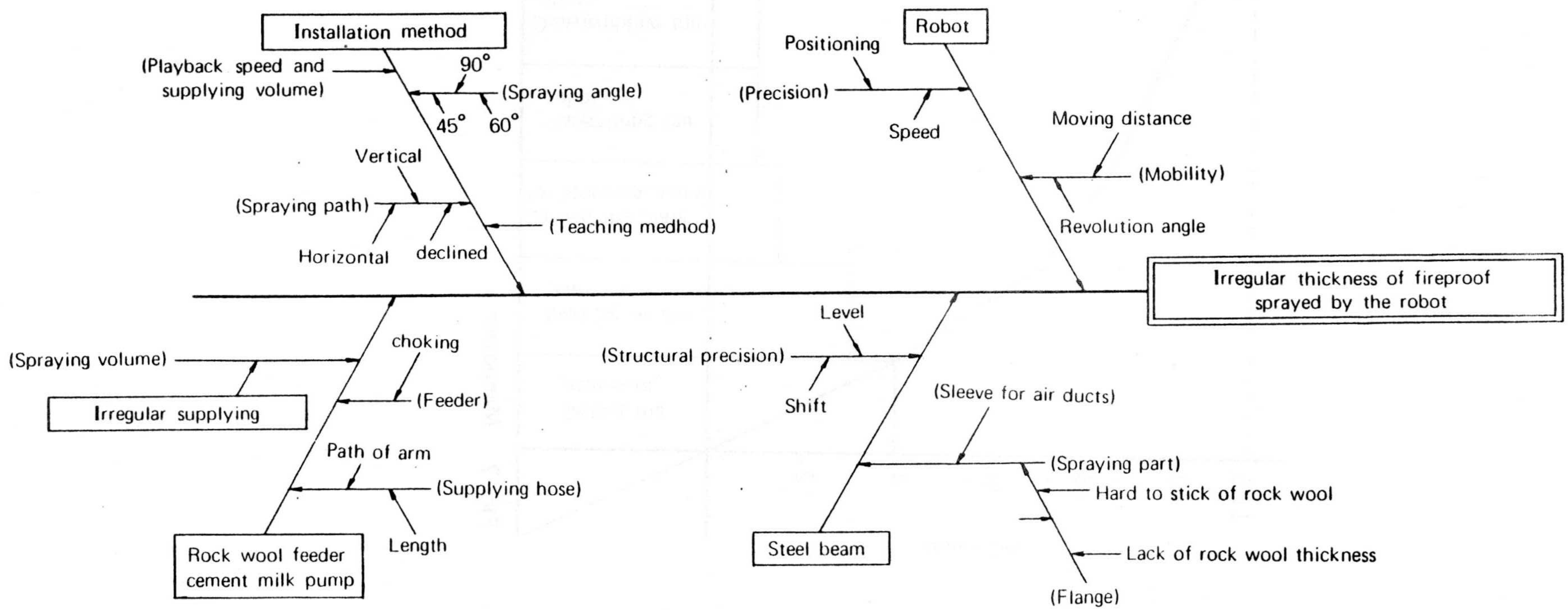



**Fig. 8 Characteristic diagram for patches of thickness**

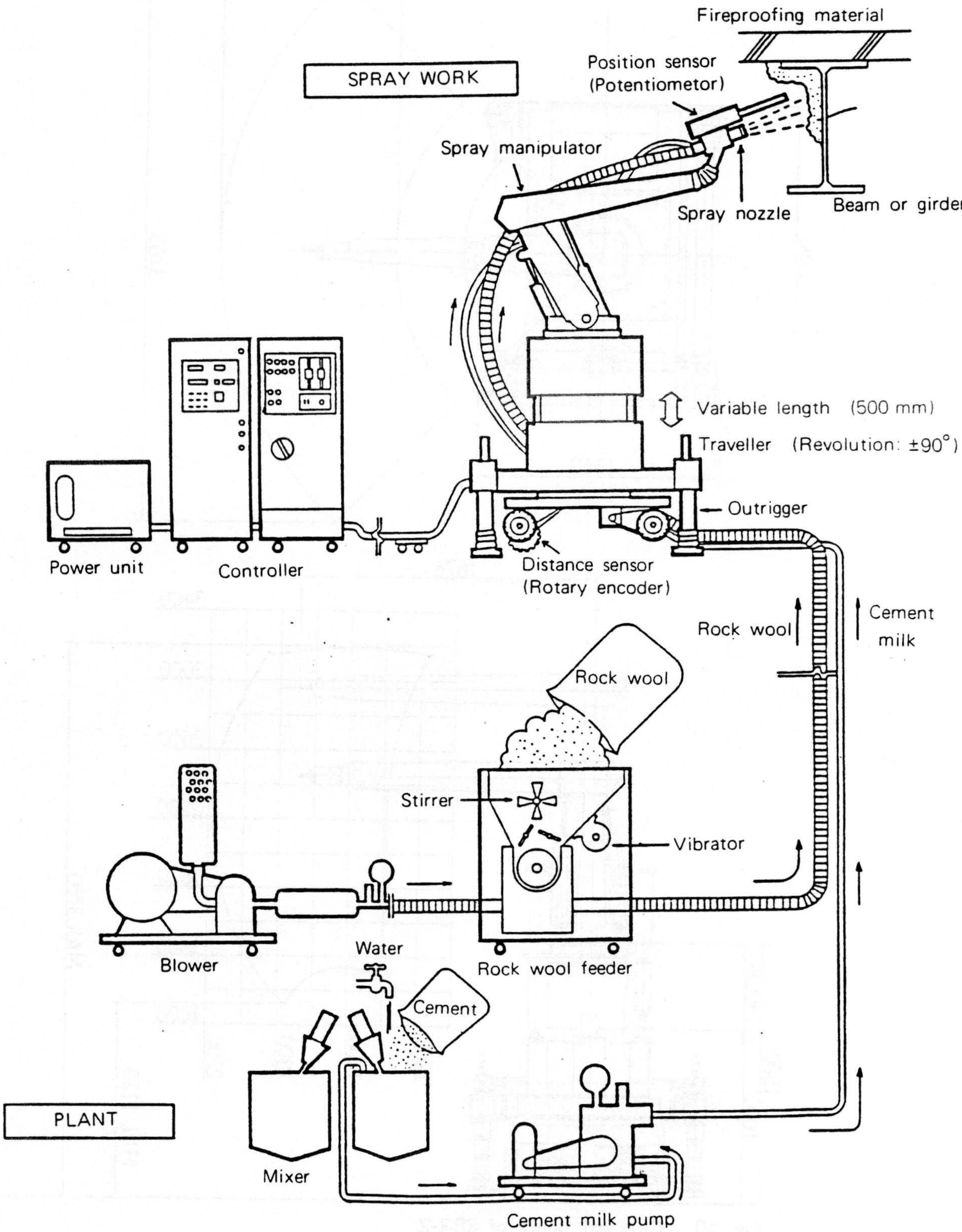



**Fig. 9 Rock wool spray system with SSR-2**

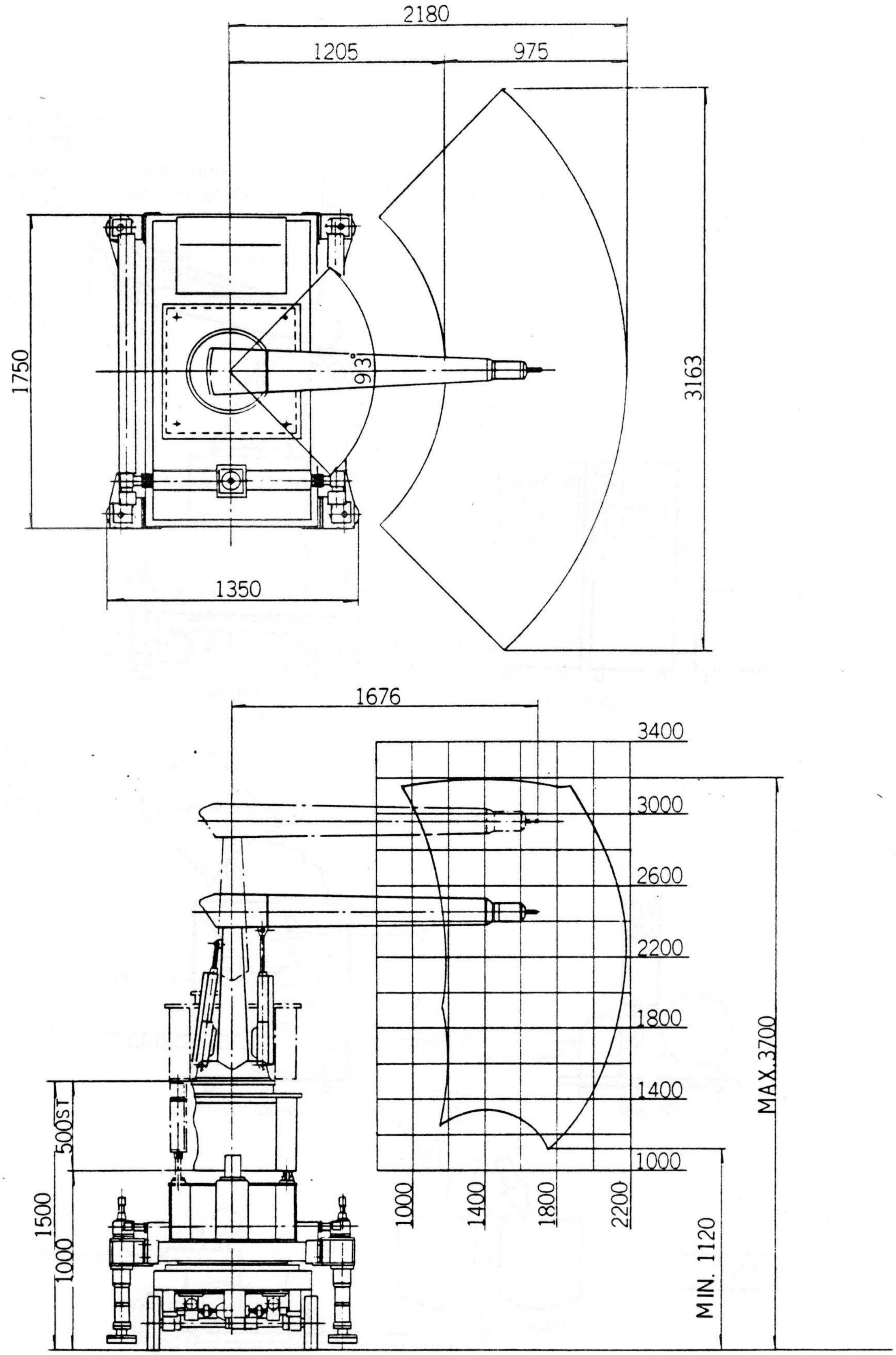



**Fig. 10 Outward figure of SSR-2**

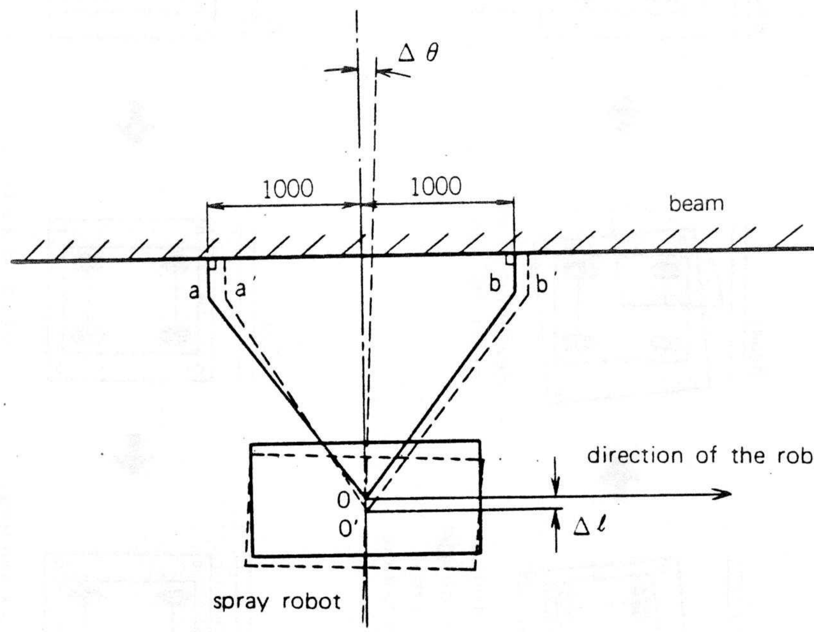



**Fig. 11 Method of the positioning**

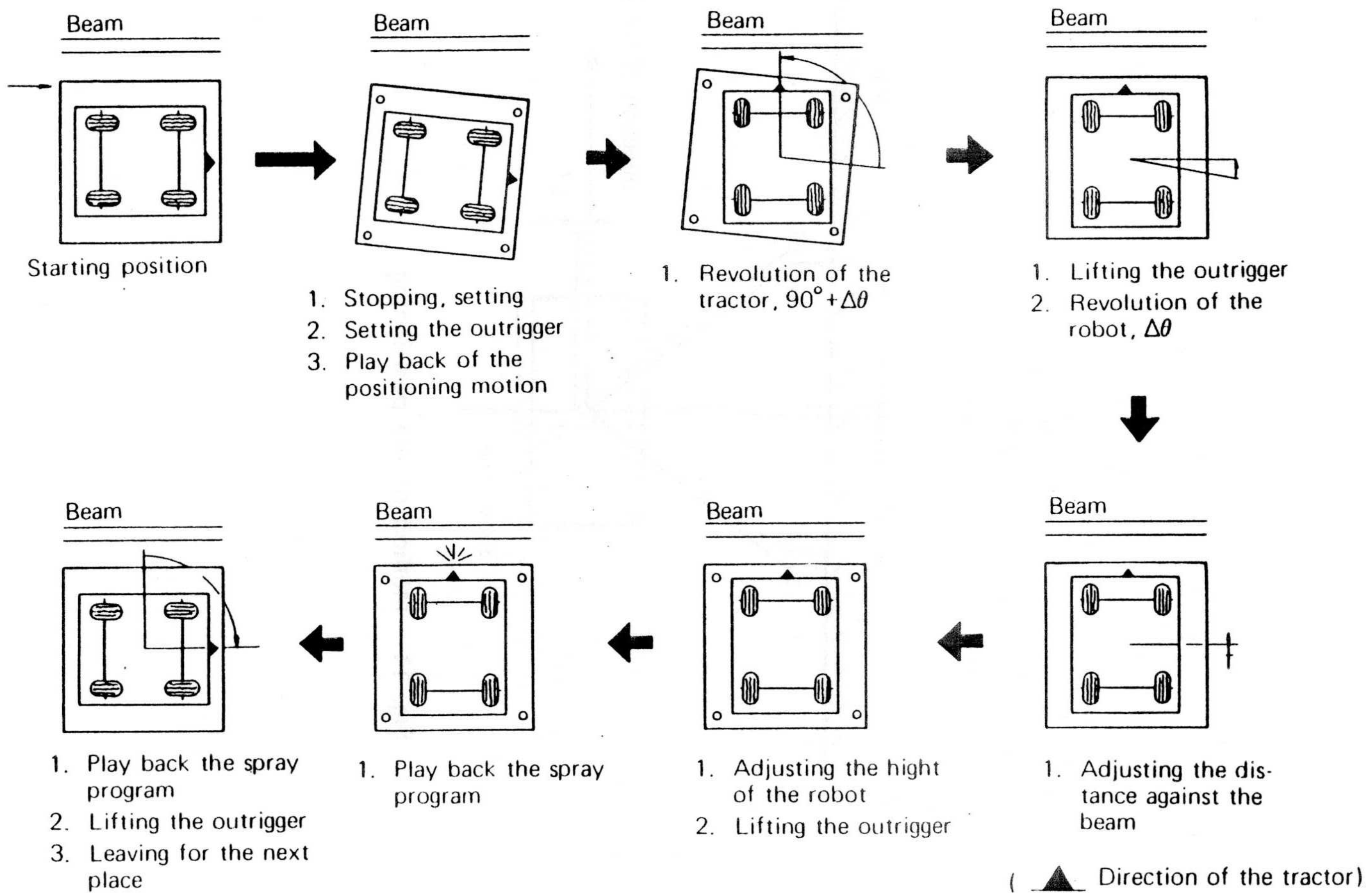



**Fig. 12 Sequence of the position adjustment**

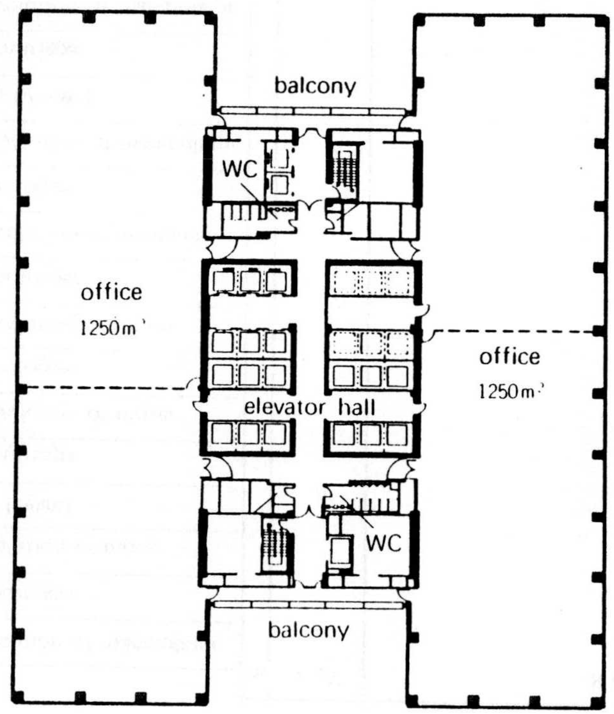
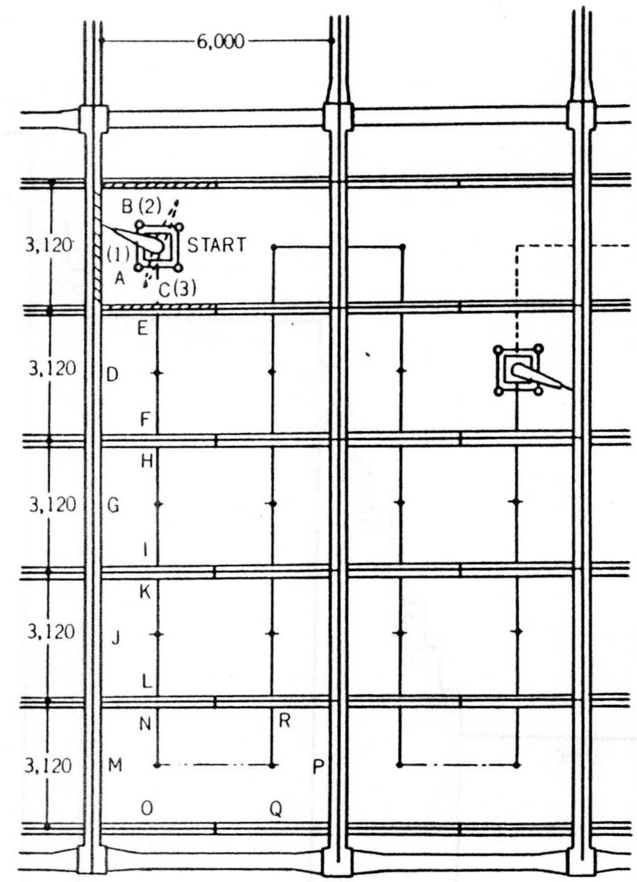



**Fig. 13 Plan of TOSHIBA Building**




Sequence

(1) Positioning & spray at A beam
(2) Turn 90° (CW) & spray at B beam
(3) Turn 180° (UCW) & spray at C beam
(4) Travelling & repeat (1) ~ (4)

**Fig. 14 Track of SSR-2**

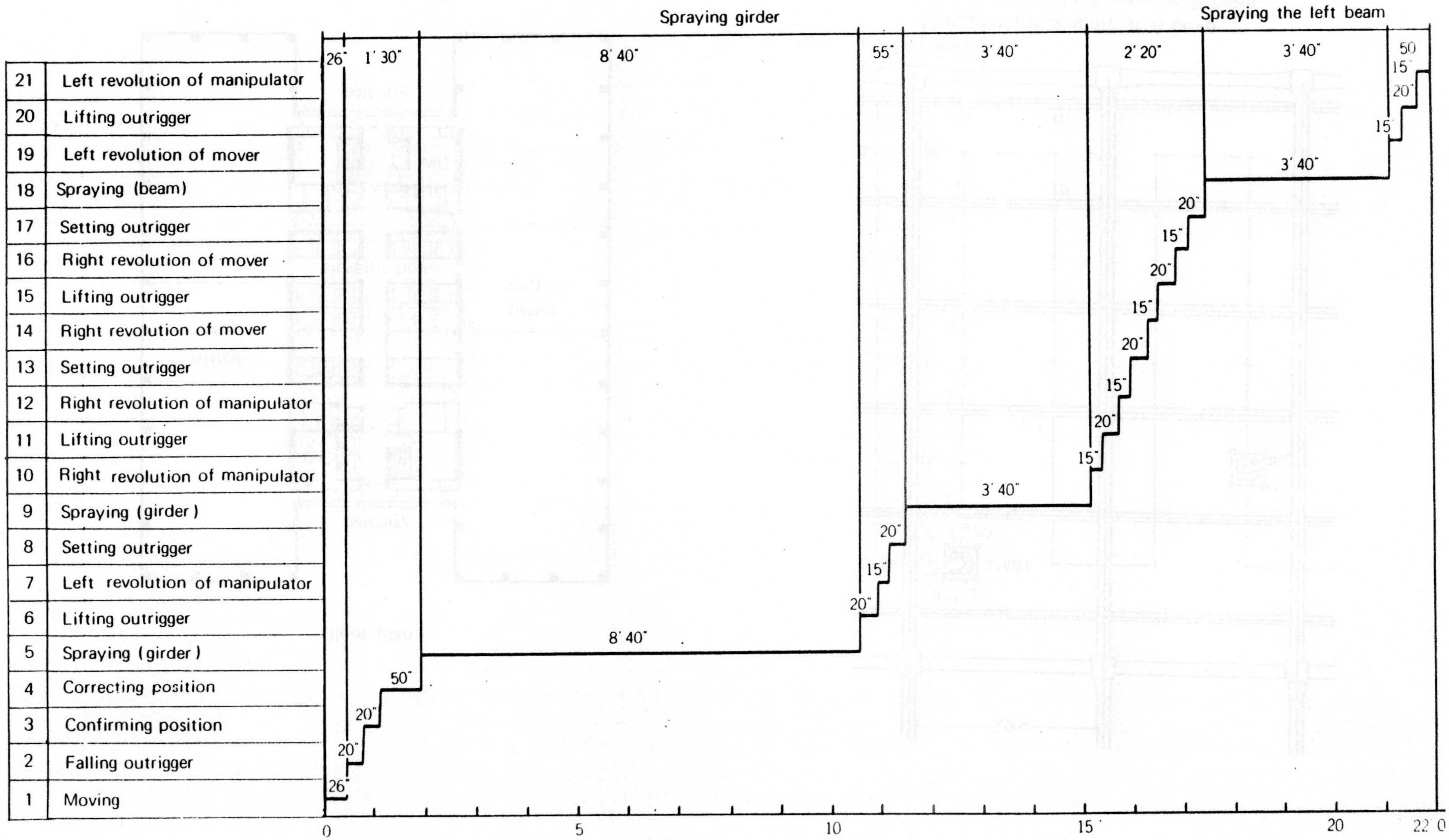



**Fig. 15 Time chart of spraying task (SSR-2)**

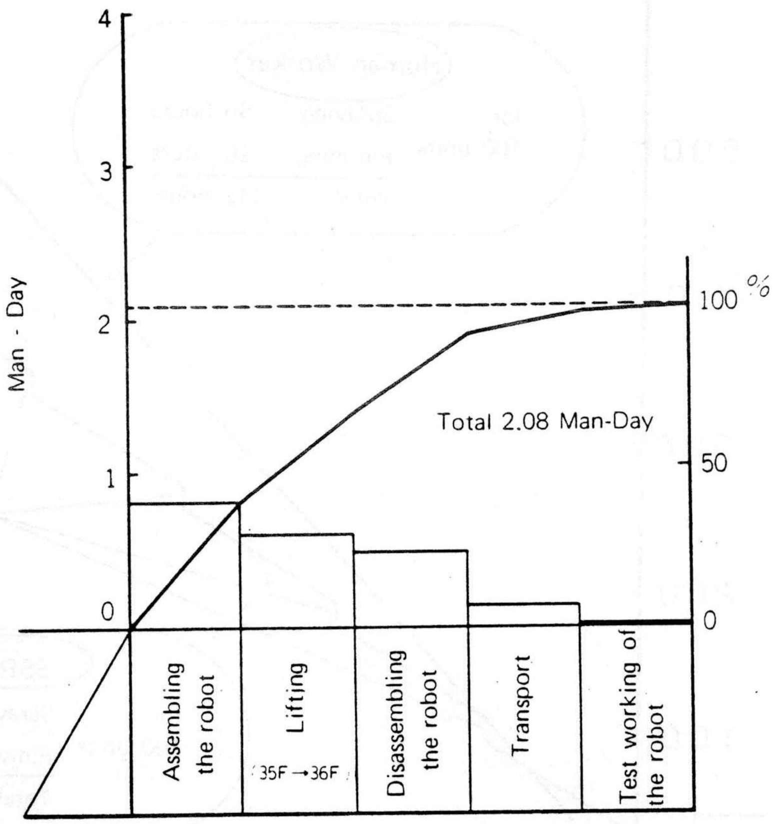



**Fig. 16 Man power (SSR-2)**

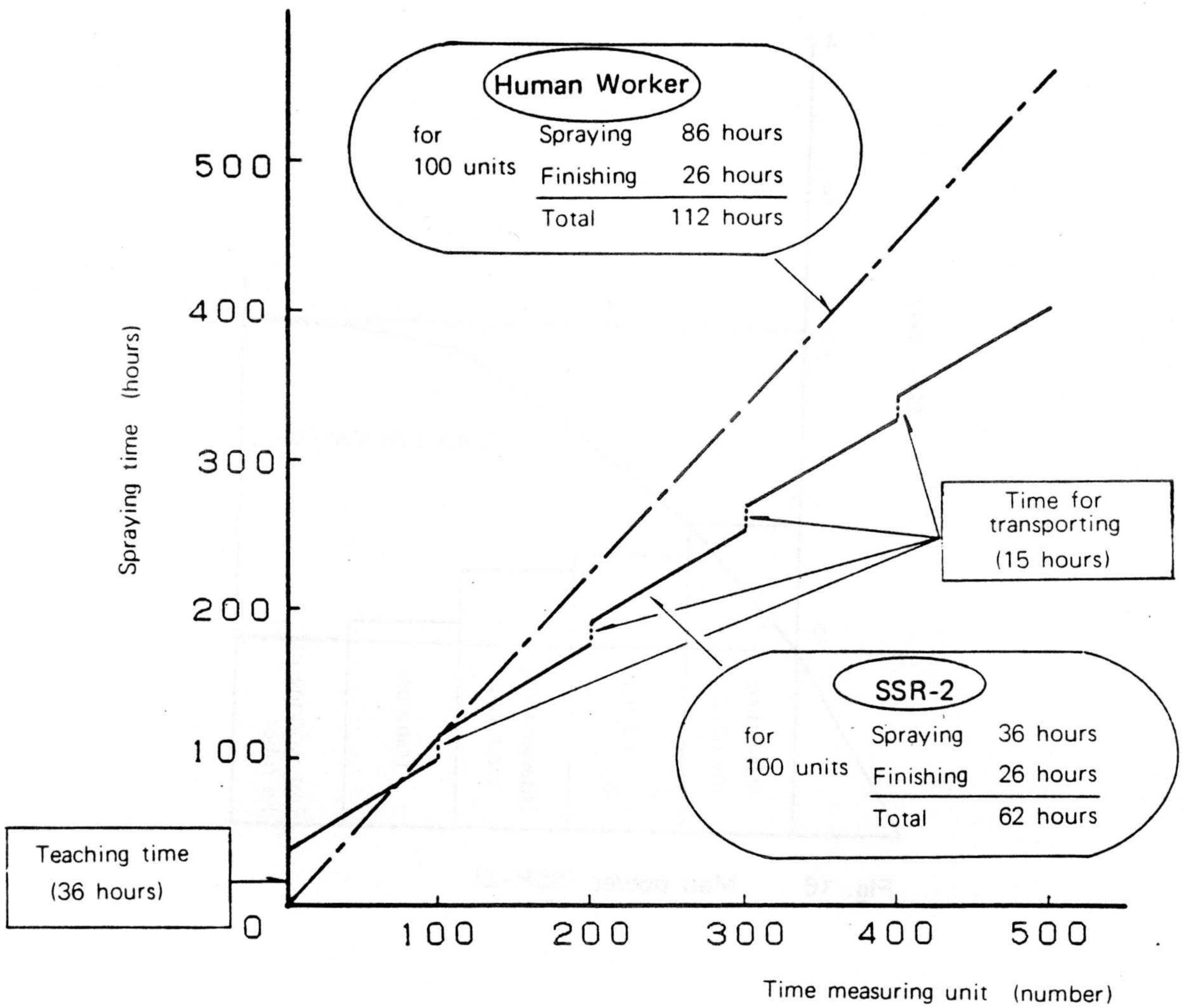



**Fig. 17 Work efficiencies of a human worker and SSR-2**

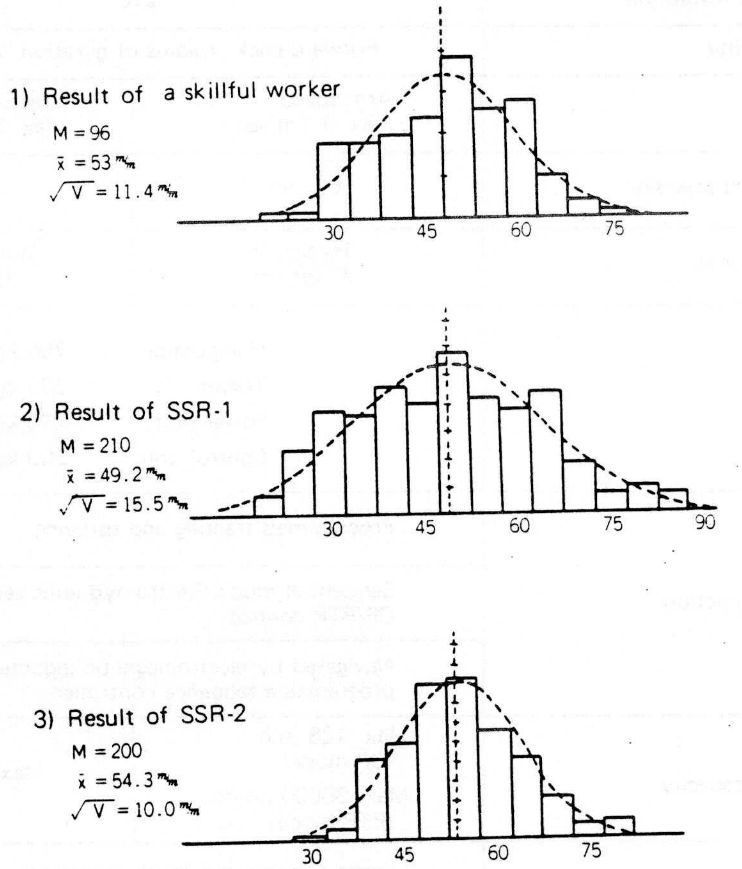



**Fig. 18 Thickness**

| | | | Manipulator | Tractor |
|---|---|---|---|---|
| Robot | Axes | Right-left turning | 100° | |
| | | In-out | 75° | |
| | | Up-down turning | 72° | |
| | | Hand up-down swing | 176° | |
| | | Hand right-left swing | 176° | |
| | | Hand revolution | 210° | |
| | | Mobility | Forward-back (radius of gyration min. 1.2m) | |
| | Speed | | Arm speed<br>max. 1.7m/sec. | Tractor speed<br>max. 2.5km/hour |
| | Positioning precision | | ±5 mm | ±20 mm |
| | Power source | | Hydraulic<br>70kgf/cm | Storage battery<br>(DC 24V) |
| | Weight | | Manipulator 700 kgf<br>Tractor 325 kgf<br>Power unit 270 kgf<br>Control unit 200 kgf | |
| Control unit | Control function | | Programmed tracting and spraying | |
| | | | Sequential mode Electro-hydraulic servo, CP/PTP control | |
| | | | Navigated by electromagnetic induction and programable sequence controller | |
| | Memory capacity | | Max. 128 min. (CP mode)<br>Max. 38000 points (PTP mode) | Max. 63 steps |
| | Safety device | | Optical sensor and touch sensor for collision avoidance<br>Automatic tractor controller<br>(Course out, Interception collision) | |

**Table-1 Specifications of SSR-1**

| | | | |
|---|---|---|---|
| Travelling device | | Degree of freedom | 3 (travelling revolution) |
| Travelling device | Travelling function | Power | hydraulic actuator |
| Travelling device | Travelling function | Travelling speed | min. 1.2m/min max. 6m/min |
| Travelling device | Travelling function | Positioning precision | ±5mm |
| Travelling device | Revolution function | Power | hydraulic actuator |
| Travelling device | Revolution function | Revolution angle | ±102.5° (manual) 1±90° (automatic) |
| Travelling device | Revolution function | Revolution speed | min. 0.4rpm, max. 2rpm |
| Travelling device | Revolution function | Revolution precision | ±0.5° |
| Travelling device | Outrigger function | Power | hydraulic actuator |
| Travelling device | Outrigger function | Elevating speed | 200mm/min |
| Travelling device | Outrigger function | Elevating precision | ±1mm |
| Travelling device | | Height | max. 500mm |
| Travelling device | | Control sequence | automatic travelling method programmed by travelling distance and revolution angle |
| Travelling device | Correcting function | Confirming precision | ±5mm |
| Travelling device | Correcting function | Method of correcting position | Detecting the position and correcting itself by position sensor at the end of the manipulator arm. |
| Manipulator | | Degree of freedom | 6 (Right-left turning, up-down traverse, In-out, Right-left swing, Up-down swing, Revolution) |
| Manipulator | | Position precision | ±5mm |
| Manipulator | | Sequential mode | Electro-hydraulic servo, CP/PTP control |
| Manipulator | | Memory capacity | CP: 4～128min PTP: 3800 points |
| Others | | Weight | 850kg (Manipulator 335kgf Tractor 470kgf) |
| Others | | Measurement | Length : 1750mm<br>Width : 1350mm<br>Height : 2500～3000mm |
| Others | | Safety function | • Collision protecting device with tape switch<br>• Optical device for detecting obstacles<br>• Alarm device with rotary light |

**Table-2 Specification of SSR-2**

| | | SSR-1 | SSR-2 |
|---|---|---|---|
| Travelling device | Travelling method | Tractor | Self-moving |
| | Induction | Electro-magnetic induction | Self-correcting (Controlled by computer) |
| | Speed | Max. 40m/min | High 6m/min<br>Low 1.2m/min |
| | Revolution | Radius of gyration min. 1.2m | 90° |
| | Actuator | Storage battery | Hydraulic actuator |
| | Precision | ±20mm | ±5mm |
| Measurement | Measurement | Length 3.80m<br>Width 1.84m<br>Height 2.4m | Length 1.75m<br>Width 1.35m<br>Height 2.5~2.9m |
| | Weight | 1025kg<br>Manipulator; 450 kgf<br>Travelling device; 250 kgf<br>Tractor; 325 kgf | 805kg<br>Manipulator; 335 kgf<br>Travelling device; 470 kgf |
| | Position control | Navigated by electromagnetic induction and programable sequence controller | Detecting the position and correcting itself by position sensor at the end of the manipulator arm |

**Table-3 Modification**