# Production cost estimation of solid oxide fuel cells

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## Abstract

Production costs of two types of solid oxide fuel cells (SOFCs) were estimated to clarify their economical prospects. In this assessment 2000 kW of SOFC capacity is assumed to be manufactured per month. Single cells of a planar type with 0.21 W/cm$^2$ are fabricated by co-firing of doctor blade layers and the separators are prepared by firing of press-moulding bodies. Stacks with 400 W consists of 20 cells and 21 separators. The materials cost of this type covers nearly 60% of the total (118 000 yen/kW). By comparison, the tubular SOFCs with 0.18 W/cm$^2$ are assumed to be made using an electrochemical vapour deposition (EVD) method or a plasma spraying (PS) method on porous support tubes. The module with 20 tubes is built up by arranging the cells in a suitable order. The support tube is fired after continuous isostatic pressing. Including the cost of support tubes, the overall costs for tubular cell systems by the EVD method and by the PS method are about 617 000 yen/kW and 293 000 yen/kW, respectively.

## Introduction

Solid oxide fuel cell (SOFC) system can directly generate electricity from chemical energy of a fossil fuel [1]. Therefore, this system is proposed as a chemical power-generating system, which is distinct from generating systems conventionally in use, hydroelectric, thermal or atomic power. Research and development on SOFC have been active over the world because of such features as high electrical generating efficiency, high power density and excellent environmental protection. Many researching and developing institutions have been elaborating several kinds of designs by various production methods aiming at higher performance and longer lifetime. In order to put SOFC systems to practical application, however, it is necessary to achieve lower initial and running costs. The production costs of SOFC have not been firmly established yet.

In this paper, the production costs of the stack segments in two types of SOFC are simulated and estimated; one is a planar type and the other is tubular.

## Preconditions and calculations of the production costs

### *Preconditions*

Before calculating costs, it is necessary to make some assumptions. The first assumption has to do with technical specifications of the estimated SOFCs. Studies on SOFCs are generally at the developing stage of several kW class modules or stacks [2, 3]. On the other hand, a variety of designs, production methods and raw materials,

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being interrelated factors, have been studied actively in many institutions and government agencies. Therefore, the costs of the two types of SOFC shown in Fig. 1 were estimated in this paper. One is a planar type and the other is tubular. Table 1 shows the technical specifications assumed for these SOFCs. In the case of the planar type, single cells with 0.21 W/cm$^2$ are fabricated by co-firing of doctor blade layers. The separating plates (separators) and interconnecting plates (interconnectors) are prepared by firing of press-moulding bodies. Stacks generating 400 W were assumed to consist of a top and bottom interconnectors enclosing 20 cells with 19 separators. On the other hand, the tubular type with 0.18 W/cm$^2$ is made using the electrochemical vapour deposition (EVD) method or the plasma spraying (PS) method on porous support tubes. The module having 20 tubes is built up in a suitable order. The support tube could be fired after continuous cold isostatic pressing. SOFC modules of these two types corresponding to 2000 kW can be manufactured per month. These specifications were determined from the results of our experiments [4, 5] and data published elsewhere [6–10].

The second assumption had to do with materials. Prices of materials per unit weight and the rate of material utilization have a direct effect upon the production costs. A yield rate is defined here as the rate of raw materials effectively used in a final or intermediate product to that supplied for production. The yield rates were determined based on the suggestions of many Japanese companies treating ceramics. Prices for several materials are listed in Table 2 on a unit weight basis. In this estimation, the materials utilized at each step of the process could not be recovered and recycled because the high performance of a SOFC is apt to be easily damaged by impurities.

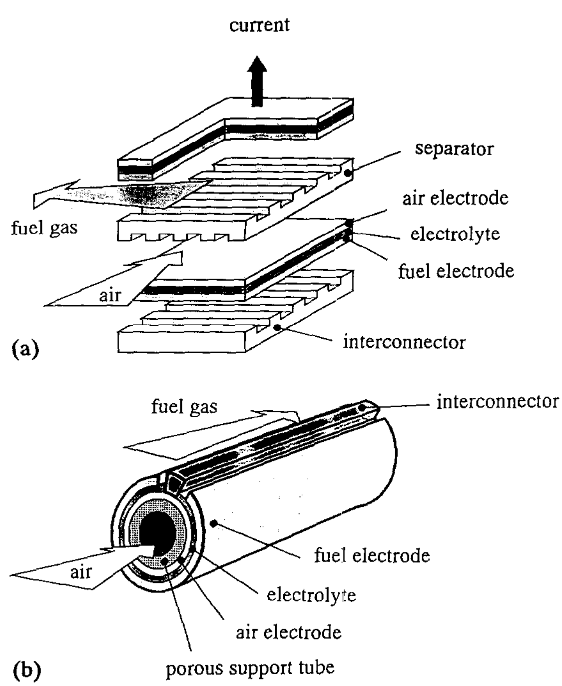


Fig. 1. The view of the planar type and tubular type SOFC used for estimation of production cost: (a) planar type, and (b) tubular type.

TABLE 1

Assumed technical specifications of SOFC

| Items of specification | Planar type | Tubular type | |
|---|---|---|---|
| Main production method | Co-firing of doctor blade layers (single cells) Firing of press-moulding bodies (separator) | Electrochemical vapour deposition (EVD) method | Atmospheric pressure plasma spraying (PS) method |
| Power density of single cell | 0.21 W/$cm^2$ (at 0.7 V, 0.3 A/$cm^2$) | 0.18 W/$cm^2$ (at 0.7 V, 0.25 A/$cm^2$) | 0.18 W/$cm^2$ (at 0.7 V, 0.25 A/$cm^2$) |
| Electrode area of single cell | 100 $cm^2$ (10 cm × 10 cm) | 290 $cm^2$ (75 cm in length)[a] | 290 $cm^2$ (75 cm in length)[a] |
| Power per stack | 400 W | 1000 W | 1000 W |
| Power per month | 2000 kW | 2000 kW | 2000 kW |
| Thickness of stack components (mm)[b] | | | |
| Electrolyte | 0.3 | 0.04 | 0.15 |
| Fuel electrode | 0.1 | 0.1 | 0.1 |
| Air electrode | 0.1 | 1.4 | 0.2 |
| Separator | 3.0 | | |
| Interconnector | 1.5 | 0.04 (width 8.0) | 0.25 (width 8.0) |

[a]Size of the support tube is 100 cm in length, 1.5 cm in an outside diameter and 1.2 mm in thickness.
[b]Density of each electrode and the support tube is 60%; that of the electrolyte, separator and interconnector is 95%.

TABLE 2

Unit prices and theoretical densities of raw materials

| Stack components of SOFC | Raw materials | Price per unit (yen/kg) | Theoretical density (g/$cm^3$) |
|---|---|---|---|
| Electrolyte | 8 mol% yttria stabilized zirconia (YSZ) | 7000 | 5.90 |
| Fuel electrode | 40 vol.% Ni–YSZ | 6000 | 6.32 |
| Air electrode | $(La_{0.8}Sr_{0.2})_{0.96}MnO_3$ | 6300 | 6.27 |
| Separator (Interconnector)[a] | $La_{0.70}Ca_{0.32}CrO_3$ ($LaCr_{0.9}Mg_{0.1}Cr_3$) | 7000 | 6.11 |
| Support tube. | Calcia stabilized zirconia | 6000 | 5.20 |
| Electrolyte for EVD process | $ZrCl_4$ | 5000 | |
| | $YCl_3$ | 24000 | |
| Interconnector for EVD process | $LaCl_3$ | 15000 | |
| | $CrCl_3$ | 5000 | |
| | $MgCl_2$ | 1250 | |

[a]The interconnector for the tubular type fabricated by the EVD method is $LaCr_{0.9}Mg_{0.1}O_3$.

The third assumption concerns the production equipment. The production equipment includes production facilities, inspecting instruments, factory building and incidental apparatus. The amount of the equipment depends on the handling capacity, which is decided from a relation between the quantity of materials and the period of usage. The production plant is constructed using machines at today's technical level. Fully automated system is not introduced in this plant. The cost of equipment is the sum of these expenditures and is depreciated at an annual interest rate of 15% over 7 years. The relation between total cost of equipment, $A$, and the payment per month, $B$, could be expressed easily by the following equation; $B = A \times 1.2125/7 \times 12$.

It is necessary to maintain this equipment and exchange expendable supplies. Maintenance expenses are set at an annual interest rate of 15% of the equipment expenditure.

The fourth assumption concerns employment workers in the production assembly lines and the clerk office. They are employed as technicians and work 8 h per day and 20 days per month at wages of 1000 yen per h. The number of workers was determined based on suggestions from Japanese companies. The expenditure on the clerk office was included in the miscellaneous expenses as the product of the number of workers and 100 000 yen per worker.

The fifth assumption concerns the power sources to operate the equipment, i.e., electricity and gases. This cost included light and heat. The expenses for workers are excluded from this section and included in the miscellaneous expenses.

The total production costs of SOFC have been calculated in the following order: (i) decision on the production process and the yield rate in each step; (ii) definite calculations of the material weight by taking the yield rate and the materials cost in a month into account. It is supposed that the acceptor rate is 95% after inspection; (iii) the estimation of cost of equipment and maintenance expenses, this expenditure is obtained from the amount of the equipment and its handling capacity, and (iv) the calculation of light and heat expenses, labour expenses and miscellaneous expenses.

*Production cost of planar type SOFC*

The production process and the yield rates of the materials on the planar type are assumed as given in Fig. 2. The several slurries of electrolyte and electrode are

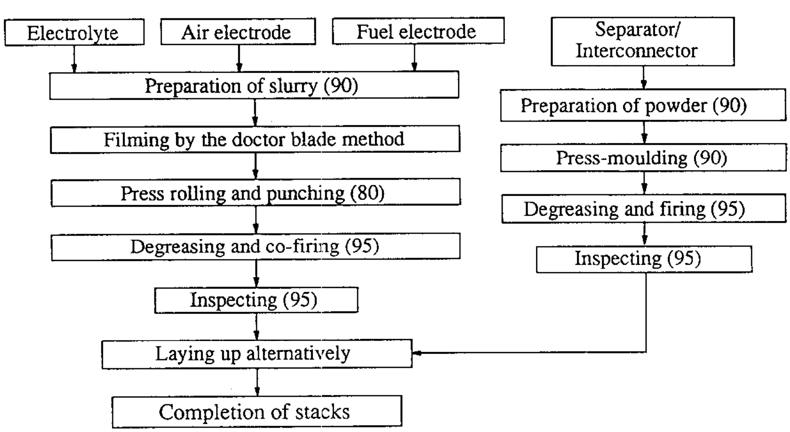


Fig. 2. The production process and yield rates of the materials for planar type SOFC. The numbers in parentheses are the rates in each process.

TABLE 3

Quanta and costs of raw materials for planar type SOFC

| | Electrolyte | Air electrode | Fuel electrode | Separator | Inter-connector | Additives |
|---|---|---|---|---|---|---|
| Weight per month (kg) | 1680 | 380 | 380 | 11030 | 580 | |
| Weight per month multiplied by yield rate (kg) | 2590 | 585 | 585 | 15000 | 790 | |
| Cost per month ($10^3$ yen) | 18100 | 3700 | 3500 | 105000 | 5500 | 700 |

prepared by blending their powders with various additives for preparations, i.e., solvent, dispersant, binder and so on, with a rotary ball milling machine. The green electrolyte films and green electrode films are spread with one doctor blade machine and three exclusive blade parts. The sheet fabricated by interposing the electrolyte film between the air electrode film and a fuel electrode film is adhered with a press rolling machine and punched finely to the prescribed size with an autopunching machine. The single cells are obtained continuously by a co-firing of these sheets in a conventional tunnel furnace. Separator powder material is mixed with other preparations and is press-moulded. The green bodies are fired in an other furnace. The stack is fabricated by laying up cells and separators alternately.

According to the supposed yield rates as shown in Fig. 2, materials costs per month could be calculated as shown in Table 3. The cost of various additives are unclear since they are developed independently by each institution.

The handling and treatment capacity determine the amount of equipment in the several production steps. Two tunnel furnaces are introduced in the firing process. One furnace is used to remove additives and to co-fire the cells, the other furnace for firing separators and should be operated in a controlled atmosphere to avoid the formation of poisonous and detrimental chromium(VI) oxide. A sample was picked up and inspected randomly from every 200 cells and separators. One sample is checked by X-ray diffraction, warp test and electrical conductivity measurement. Table 4 shows the items of equipment, their cost and maintenance expenses including expendable supplies. A request for more flat plates with more parallel surfaces with rigorous accuracy raises the quality and price of the metal mould for the press-moulding machine and for the punching machine. The expenses for these are set at about 14 300 000 yen per month, considering the balance between quality and expenditure.

The furnace consumes the largest amount of electricity in the production assembly line. The electrical charge for the two furnaces per month, at a rate of 12 yen per unit kWh, is 6 200 000 yen per month. Heat and light expenses are 7 100 000 yen. Labour expenses and miscellaneous expenses are 48 000 000 and 3 100 000 yen, respectively, for the plant with 31 workers.

*Production cost of the porous tube*

The tubular type SOFC is mainly constructed on a porous support of calcia stabilized zirconia (CSZ) powder. CSZ powder is mixed with various additives and moulded by a continuous cold isostatic pressing (CIP) method. One end of the tube is closed and the other is open. The production process, with the yield rates of each

TABLE 4

Costs of equipment and maintenance expenses for planar type SOFC ($10^3$ yen/month)

| Items of machine | Cost of equipment | | | | | Maintenance expenses |
|---|---|---|---|---|---|---|
| | Electrolyte | Air electrode | Fuel electrode | Separator (interconnector) | Subtotal | |
| Ball milling (for 100 kg) | 8000 (×2) | 8000 | 8000 | | 68000 | 900 |
| (for 300 kg) | | | | 1200(×3) | | |
| Doctor blade | | 140000 | | | 140000 | 200 |
| Press rolling | | 50000 | | | 50000 | 600 |
| Autopunching | | 30000 | | | 30000 | 7550[a] |
| Press moulding | | | | 80000 | 80000 | 8150[a] |
| X-ray diffraction | | 10000 | | 10000 | 20000 | 300 |
| Warp testing | | 15000 | | 15000 | 30000 | 400 |
| Electric conductivity measurement | | 50000 | | 50000 | 100000 | 1200 |
| Tunnel furnace | | 100000 | | 100000 | 200000 | 2500 |
| Factory building | | | 300000 | | 300000 | 4200 |
| Total[b] | | | | | 14700 (1018000) | 26000 |

[a]These expenses include the expenditure of expendable supplies.

[b]The number, 14700, in this Table shows the cost per month and the number in parentheses is the true sum of the equipment cost.

step, is shown in Fig. 3. Based on the assumed yield rates, the monthly demand of CSZ powder is 7600 kg by weight and the materials costs is 46 200 000 yen per month. The green tubes are fired in the furnace which is large than that used in the production process of planar SOFC. The outer surface of the tubes is mechanically finished after sintering. They are exposed to ultrasonic washing to remove soil and cutting refuse. Table 5 shows the machines, their cost and their maintenance expenses. Maintenance expenses are added to the expenditure for consumable supplies such as a moulding tube and bar at 110 yen per complete set. The heat and light expenses are treated in a similar manner to the case of the planar type. The 600 kWh furnace consumes

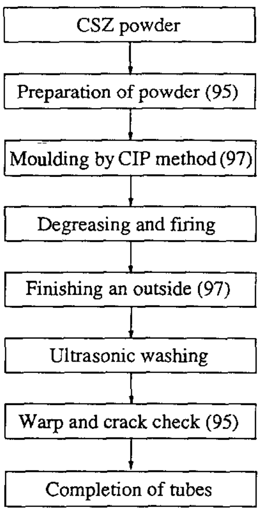


Fig. 3. The production process and yield rates for calcia stabilized zirconia (CSZ) tubus. The numbers in parentheses are the rates in each process.

TABLE 5

Equipment and maintenance expenses for support tube ($10^3$ yen/month)

| Items of machine | Cost of equipment | Maintenance expenses |
|---|---|---|
| Ball milling | 12000(×2) | 300 |
| Cold isostatic pressing | 200000(×2) | 9700[a] |
| Tunnel furnace | 250000 | 3100 |
| Finishing by an outside | 10000(×3) | 400 |
| Ultrasonic washing | 50000 | 600 |
| Cracks and warp checking | 15000 | 200 |
| Factory building | 300000 | 3800 |
| Total[b] | 15400<br>(10690000) | 18100 |

[a]These expenses include the expenditure of expendable supplies.
[b]The number, 15400, in this Table shows the cost per month and the number in parentheses is the true sum of the equipment costs.

electricity costing about 6 200 000 yen per month. Forty workers are necessary to operate this plant continuously.

*Production cost of tubular type SOFC fabricated by the electrochemical vapour deposition method*

The EVD technique has been developed originally by the Westinghouse Electric Company for SOFC [11]. Eight mol% yttria stabilized zirconia (8YSZ) electrolyte which is also used for fixing the fuel electrode is deposited by the EVD method at a deposition rate of 60 $\mu$m/h and, for the interconnector, is deposited at 40 $\mu$m/h. The production process consists of the stages shown in Fig. 4:

(i) sand blasting of the support tube surface to improve the adhesion of the air electrode slurry;

(ii) deposition of the air electrode; the tubes are fired to remove greases and to sinter the air electrode after dipping into the slurry; then the outer tubes are mechanically finished by an external machine to make the thickness of the electrode uniform, and

(iii) coating process by the EVD method; the continuous EVD apparatus is composed of eight units; each unit has a furnace, gas-pipe arrangements and controller, and is able to produce 200 tubes per batch; this apparatus is used for deposition of both 8YSZ and the interconnector layers.

The yield rates of the cell components coated by the EVD method are shown in Fig. 4. The yield rate of 5% in the EVD technique was based on the general yield of chemical vapour deposition, since the relation between the gas concentration and the deposition rate was unknown. Table 6 gives the materials costs. On the basis of the above-mentioned assumptions, the costs of equipment and maintenance expenses are given in Table 7, in which the maintenance expenses of the EVD apparatus are expected to be 20% per year. Production of this SOFC requires electricity for the furnace and gas for the EVD plus light and heat expenses. The sum of these expenses

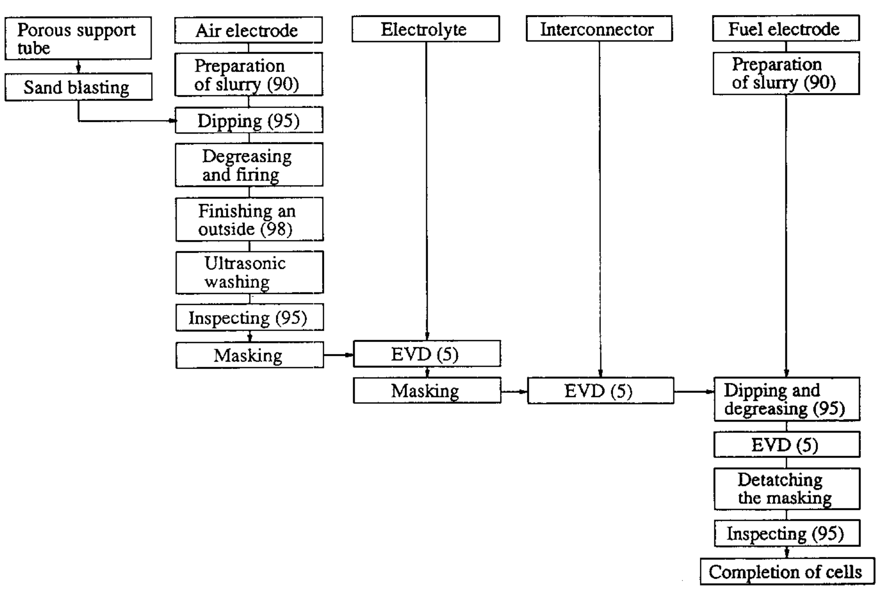


Fig. 4. The production process and yield rates of the materials for tubular type SOFC fabricated by the EVD method. The numbers in parentheses are the rates in each process.

TABLE 6

Quanta and costs of raw material for tubular type SOFC fabricated by the EVD method

| | Air electrode[a] | Interconnector | | | Electrolyte | | Fuel electrode | | | Sand-blasting materials |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $LaCl_3$ | $CrCl_3$ | $MgCl_2$ | $ZrCl_4$ | $YCL_3$ | Ni–YSZ[a] | $ZrCl_4$ | $YCl_3$ | |
| Weight per month (kg) | 7520 | 840 | 520 | 40 | 640 | 120 | 560 | 640 | 120 | 4000 |
| Weight per month multiplied by yield rate (kg) | 9930 | 17640 | 10920 | 840 | 13440 | 2520 | 690 | 13440 | 2520 | 4440 |
| Cost per month ($10^3$ yen) | 63000 | 264600 | 54600 | 1100 | 67500 | 60500 | 4100 | 67500 | 60500 | 2300 |

[a]These materials include various additives for preparation of the slurry.

TABLE 7

Costs of equipment and maintenance expenses for the tubular type SOFC by the EVD method ($10^3$ yen)

| Items of machines | Cost of equipment | | | | | | Maintenance expenses |
|---|---|---|---|---|---|---|---|
| | Air electrode | Interconnector | Electrolyte | Fuel electrode | Fixation of fuel electrode | Subtotal | |
| Ball milling (for 100 kg) | | | | 8000 | | | |
| (for 400 kg) | 15000 | | | | | 23000 | 300 |
| Dipping tank | 50000 | | | 30000 | | 80000 | 1000 |
| Dryer | 20000 | | | 20000 | | 40000 | 500 |
| Tunnel furnace | 150000 | | | | | 150000 | 2000 |
| Finishing an outside | 30000 | | | | | 30000 | 4900[a] |
| Sand blasting | 15000 | | | | | 15000 | 200 |
| Ultrasonic washing | 50000 | | | | | 50000 | 600 |
| EVD contrivance | | 800000 | 500000 | | 500000 | 1800000 | 30000 |
| Electric conductivity measurement | | | 20000 | | | 20000 | 300 |
| Gas leakage check | | | 50000 | | | 50000 | 600 |
| Factory building | | | 300000 | | | 300000 | 3800 |
| Total[b] | | | | | | 36700 (2558000) | 44200 |

[a]These expenses include the expenditure of expendable supplies.

[b]The number, 36700, in this Table shows the cost per month and the number in parentheses is the true sum of the equipment cost.

is about 34 100 000 yen per month. Workers are assigned to the process of air electrode slurry or to the EVD process. In the EVD process, they have jobs of attaching the tubes to the apparatus and masking the unnecessary area on the tubes. Labour costs and miscellaneous expenses are listed in detail in Table 8.

*Production cost of tubular type SOFC fabricated by the plasma spraying method*

The PS method has been employed for the deposition of materials with high melting points on the substrates as heat and/or corrosion resistant layers. These applications are mainly in aeronautical, industrial and chemical fields, and also in the recent development of SOFC [12]. The atmospheric pressure PS method is assumed to be successful in depositing films without gas leakage, in this paper. The process and yield rates of this SOFC are shown in Fig. 5. The porous tubes are sequentially coated with the air electrode, electrolyte, interconnector and fuel electrode. Only the

TABLE 8

Labour expenses and miscellaneous expenses for the tubular type SOFC fabricated by the EVD method

| Cell components | Labour expenses ($10^3$ yen/month) | Number of workers | Miscellaneous expenses ($10^3$ yen/month) |
|---|---|---|---|
| Air electrode | 32000 | 20 | 2000 |
| Interconnector | 51200 | 32 | 3200 |
| Electrolyte | 83200 | 52 | 5200 |
| Fuel electrode | 25600 | 16 | 1600 |
| Fixation of fuel electrode | 83200 | 52 | 5200 |
| Inspecting | 25600 | 16 | 1600 |
| Total | 300800 | 188 | 18800 |

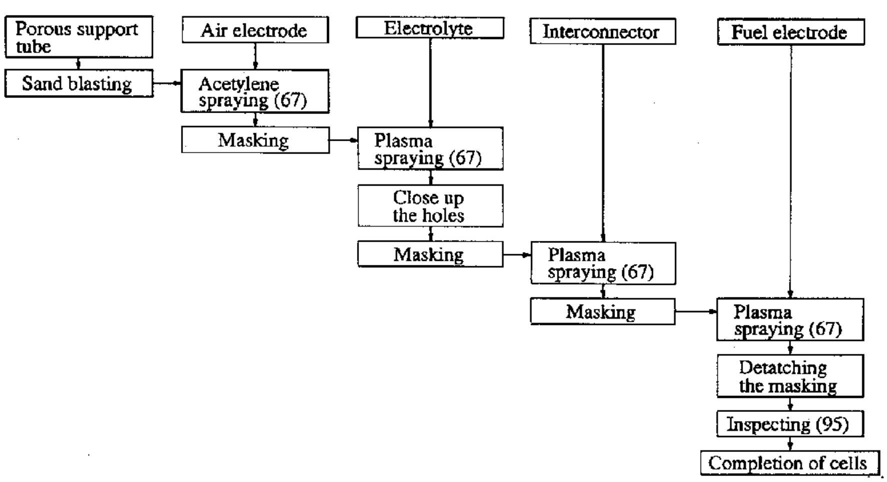


Fig. 5. The production process and yield rates of the materials for tubular type SOFC fabricated by the PS method. The numbers in parentheses are the rates in each process.

TABLE 9

*Quanta and costs of raw material for the tubular type fabricated by the PS method*

| | Electrolyte | Air electrode | Inter-connector | Fuel electrode | Sand-blasting material | Closing up the holes |
|---|---|---|---|---|---|---|
| Weight per month (kg) | 1100 | 1360 | 480 | 580 | 2200 | |
| Weight per month multiplied by yield rate (kg) | 1730 | 2150 | 760 | 910 | 2360 | |
| Cost per month ($10^3$ yen) | 10900 | 15000 | 5300 | 5500 | 400 | 1300 |

air electrode is deposited by the acetylene method. The tubes are sand blasted before depositing the air electrode. Uncoated regions are covered with a masking plate. After the electrode was sprayed, the micropores are closed with a specific material. The yield rate of the spraying process is 67%, that is the maximum level attained by currently available PS systems. Thus, we assumed that the powder of materials necessary for PS systems is 1.58 times as much weight as the deposited layers. The materials costs is shown in Table 9. In the case of mass production of SOFC by the spraying method, each spraying machine is used only for one component. The number of the production assembly line should be determined so as to finish the most time-consuming spraying step effectively. The deposition of electrolyte takes the longest duration, 10 min. Each line consists of an acetylene spraying machine, three PS machines, a tunnel furnace, a dust collecting arrangement and some peripheral facilities. To produce the previously mentioned SOFC, 10 lines are necessary. Table 10 summarizes the equipment and maintenance expenditures. The operation of the PS machines requires electric power and several gases. Compressors, dust collectors and the furnaces are also operated by electricity. Table 11 details these expenses. Workers are needed to attach the tubes at the assembly lines, to mask and demask the plate and to supply the material powders. Three workers are assigned to each line, three of them to the sand blast process and four to the inspecting section. The expenses for 155 workers are 248 000 000 yen per month. The total cost of expendable supplies (35 200 000 yen per month) consists of 100 000 yen for the nozzles of the blasting machines, 30 900 000 yen for the nozzles and electrodes of the PS machines and 4 200 000 yen for masking plates.

## Results and discussions

*Comparison of the estimated costs*

Data obtained through this estimation study is given in Table 12 and in Fig. 6. The production cost of the planar type SOFC is about 118 000 yen per kW and is the cheapest all of the types. The materials cost of the planar type covers nearly 60% of the total because of the large consumption of expensive materials, especially for the separator. This cost can be reduced by decreasing the thickness of the separator and/or the electrolyte. Labour expenses, which form the second largest part in this type, 20%, are cheaper than those for other types.

TABLE 10

Costs of equipment and maintenance expenses for tubular type SOFC by the PS method ($10^3$ yen)

| Items of machines | Cost of equipment | | | | | Maintenance expenses |
|---|---|---|---|---|---|---|
| | Air electrode | Electrolyte | Interconnector | Fuel electrode | Subtotal | |
| Sand blasting | 5000(×3) | | | | 15000 | 300[a] |
| Acetylene spraying | 2500(×10) | | | | 25000 | 300 |
| Correcting dust | | 12000(×10) | | | 120000 | 1500 |
| Spraying robot | 5000(×10) | 5000(×10) | 5000(×10) | 5000(×10) | 200000 | 2500 |
| Plasma generator | | 25000(×10) | 25000(×10) | 25000(×10) | 750000 | 9400 |
| Autospraying machine | | 2000(×10) | | | 200000 | 2500 |
| Gun for spraying | | 2100(×10) | 2100(×10) | 2100(×10) | 63000 | 30900[a] |
| Tunnel furnace | | 150000 | | | 150000 | 1900 |
| Gas leakage check | | 20000 | | | 20000 | 300 |
| Electric conductivity measurement | | 50000 | | | 50000 | 600 |
| Factory building | | 300000 | | | 300000 | 3800 |
| Total[b] | | | | | 27300 (1893000) | 53900 |

[a]These expenses include the expenditure of expendable supplies.
[b]The number, 27300, in this Table shows the cost per month and the number in parentheses is the true sum of the equipment cost.

TABLE 11

Heat and light expenses for the PS process

| | Term of spraying (min) | Gas | | Electricity | | Subtotal ($10^3$ yen/month) |
|---|---|---|---|---|---|---|
| | | (yen/h) | ($10^3$ yen/month) | (yen/h) | ($10^3$ yen/month) | |
| Air electrode | 5 | 1500 | 5200 | 12 | 120 | 5300 |
| Electrolyte | 10 | 2000 | 14000 | 1250 | 8800 | 22800 |
| Interconnector | 3.5 | 2000 | 4900 | 1250 | 2600 | 8000 |
| Fuel electrode | 3 | 2000 | 2600 | 1250 | 2600 | 5200 |
| Compressor | | | | 900 | 600 | 600 |
| Correcting dust | | | | 660 | 500 | 500 |
| Furnace | | | | 4200 | 3000 | 3000 |
| Total | | | 26700 | | 18700 | 45400 |

TABLE 12

Items of production cost (yen/kW)[a]

| Items | Planar type | Tubular type by the EVD method | Tubular type by the PS method | Porous support tube (20 tubes) |
|---|---|---|---|---|
| Cost of equipment | 7000 (6) | 16000 (3) | 14000 (6) | 8000 (10) |
| Maintenance expenses | 13000 (11) | 22000 (4) | 28000 (13) | 10000 (12) |
| Material cost | 68000 (58) | 324000 (60) | 19000 (9) | 22000 (29) |
| Labour expenses | 25000 (21) | 151000 (28) | 123000 (57) | 32000 (42) |
| Miscellaneous expenses | 1000 (1) | 11000 (2) | 8000 (4) | 2000 (3) |
| Heat and light expenses | 4000 (3) | 16000 (3) | 24000 (11) | 3000 (4) |
| Total | 118000 | 540000 | 216000 | 77000 |

[a]The number in parentheses shows percentage of the total cost.

On the other hand, costs for the EVD tubular type, consisting of 20 tubes, and the PS tubular type are respectively 617 000 and 293 000 yen per kW when 20 tubes are priced. It is noted that the manufacturing cost of the tubular type by the EVD technique is very expensive. All chloride materials, expect the air electrode, are very expensive, whereas the material utilization is very small (5%). Labour expenses are highest of all the estimated processes. The production cost of the PS tubular type is about two times that of the planar type. The labour expenses become 60%. It is evident that the materials cost is low due to high utilization of material as for the planar type. Thin layers lead to small quantities of materials.

The single cells and the separators are prepared successively on the individual assembly lines. The lines do not require any manual operation. In the case of the tubular SOFC, however, several materials are deposited individually on a tube.

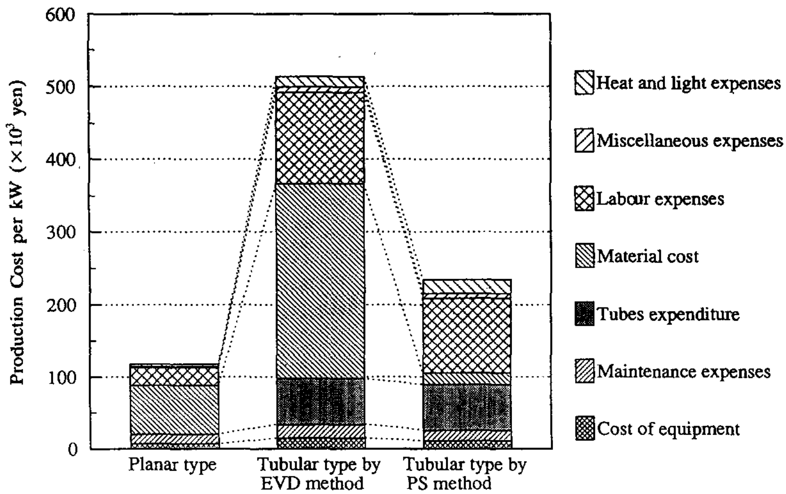


Fig. 6. Production costs of several SOFCs with 0.21 W/cm$^2$.

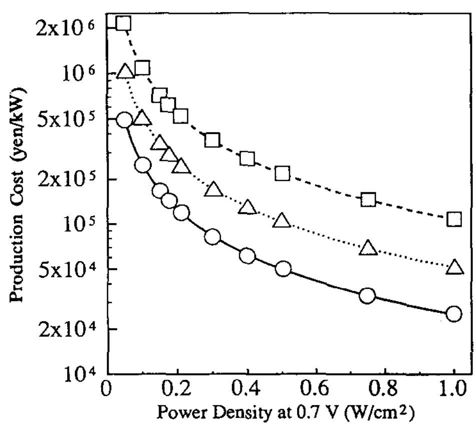


Fig. 7. Dependence of power density on production cost of several types of SOFC: (○) planar type; (△) tubular type by PS method consisting of 20 tubes, and (□) tubular type by EVD method consisting of 20 tubes.

*Practical application*

In Japan, the current initial cost of a cogeneration system (CGS) is set around 200 000 to 300 000 yen per kW [13]. However, if CGS improves in commercialization and compactness, this cost is expected to decrease to ~100 000 yen per kW. This assumption is able to be applied to the on-site type and to big scale power plants. Accordingly, the electric power generation part of the costs in the SOFC system estimated, in this paper, is requested to cost less than 50 000 yen per kW. Figure 7 shows the relation between cost and power density. The production costs decrease sharply with power density up to 0.5 W/cm$^2$, however, the slope of the cost reduction becomes small above 0.5 W/cm$^2$. In the case of the planar type SOFC, a sufficiently profitable power density for commercial application is 0.5 W/cm$^2$. On the other hand, there is a practical difficulty with the tubular type from the economical view.

*Reduction of the production cost*

Reduction of the production costs depends on the materials cost and labour expenses. Especially, decrease in quantities of raw materials is directly effective in reducing not only materials cost but also the other cost and expenses. The stack components should be as thin as possible from the cost reduction point of view. Reduction of labour expenses is possible by operating the assembly lines by automation and by employing cheap labour. In this section the materials cost is also considered.

According to Fig. 8, reduction of the separator thickness of the planar type is effective in cost reduction. The production cost of the planar type is calculated as shown in Table 13 based on the assumption that the thickness of the separator and the interconnector are a half and two-thirds of the original specification, respectively.

In the tubular type, the porous tube of the air electrode material is employed instead of a CSZ tube. These tubes have a superior performance as a supporter for the SOFC, as air electrode and as electric conductor. If the production of this tube is similar to that of the tubular type, the cost for depositing the air electrode can be eliminated. Table 14 shows the cost of the tubular type with the air electrode support tube. The cost of EVD and PS is curtailed 52 000 and 38 000 yen/kW as a result of these estimations, respectively.

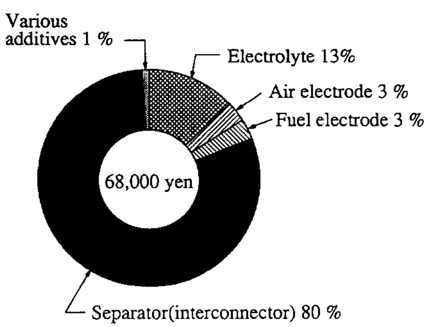


Fig. 8. Materials cost per kW of planar type SOFC covering to nearly 60% of the total production cost.

TABLE 13

Production costs of the planar type SOFC after reduced thickness of separator and interconnector ($10^3$ yen/month)

| | Curtailed segments | | Production cost after reduced thickness |
|---|---|---|---|
| | Separator | Interconnector | |
| Cost of equipment | 300 | 100 | 14300 |
| Maintenance expenses | 250 | 50 | 25700 |
| Material cost | 50300 | 1800 | 84400 |
| Labour expenses | 700 | 100 | 47400 |
| Miscellaneous expenses | | | 3100 |
| Heat and light expenses | | | 7100 |
| Total | 51550 | 2050 | 182000 |

TABLE 14

Cost of tubular type SOFC by the EVD method or by the PS method applied air electrode tube ($10^3$ yen/month)

| | Tubular type by the EVD method | | Tubular type by the PS method | |
|---|---|---|---|---|
| | Curtailed segment | Production cost | Curtailed segment | Production cost |
| Cost of equipment | 6100 | 30600 | 5200 | 22100 |
| Maintenance expenses | 5600 | 38400 | 4100 | 54100 |
| Material cost[a] | 63000 | 753900 | 11100 | 195500 |
| Labour expenses | 39100 | 261700 | 64500 | 183500 |
| Miscellaneous expenses | 2400 | 16400 | 4000 | 11500 |
| Heat and light cost | 5000 | 29100 | 6400 | 39000 |
| Total | 121200 | 1130100 | 95400 | 509200 |

[a]Material cost includes the tubes expenditure.

## Conclusions

Conclusions obtained from this cost estimating study on SOFC are as follows:

1. The production cost of the planar type SOFC is the cheapest. If the performance is improved up to 0.5 W/cm$^2$ and the components become thinner, this type can be put into commercial application.

2. The tubular type SOFC, especially fabricated by the EVD method, is very expensive. Judging from the economical points of view, the cost of tubular types cannot be accepted for practical application at the present stage.

3. Materials and labour expenditure occupy large parts of the overall production cost, but room for cost reduction still exists.

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