

# Transformer-Rectifier Package (S-Former) for Aluminum Smelting

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## 1. Introduction

At the time when aluminum was discovered in 1807, it was predicted that aluminum could be decomposed by electrolysis. But, at that time, it was extremely difficult to obtain inexpensive and powerful electric energy for this purpose. In the 1860s, inexpensive and stable DC electric energy was made available by the achievement of Mr. Siemens of Germany and Mr. Gram of Belgium. Thus, a means for performing aluminum smelting by electrolysis was established.

In this process, bauxite, a raw material of aluminum, is first dissolved by a caustic soda, and the alumina is extracted. Next, the alumina is dissolved using cryolite as a solvent, and is smelted by electrolysis using a DC power source. This method (aluminum smelting) replaced the metal deoxidization methods used previously. Aluminum smelting has been utilized industrially since 1888 in Europe and North America. In Japan, aluminum smelting has been utilized since 1894.

Aluminum smelting requires a high DC current for the electrolytic process. Generally, a high DC current is obtained from an AC power source using rectifier equipment. As the result of technical innovation from the 1960s, older type rectifier equipment, i.e., rotary converters, mercury rectifiers and contact converters,

have been replaced by semiconductor rectifiers using selenium and silicone technology. Recently, even higher voltage and higher current rectifier equipment has been realized thanks to the development of semiconductor elements for this purpose.

Since 1959, Fuji Electric has received 74 orders for rectifier equipment consisting of transformers and rectifiers. Presently, we have the top market share in the world. The rectifier equipment we supplied for MOZAL (Mozambique) started operation in 2000 and holds the world record for unit capacity of 1,330 V, 100 kA DC and 133 MW. Figure 1 shows current carrying test on the equipment at the factory.

In this paper, we explain the market requirements and recent technical trends of the rectifier equipment for aluminum smelting.

## 2. Features of Transformer-Rectifier Package for Aluminum Smelting

As the aluminum smelting industry consumes huge amounts of electric energy, the conservation of electric energy has always been a prime target for improvement. For this purpose, the development of smelting has emphasized the use of larger pots, improved electrode construction, and automatic computer control of the electrode position. Measures for balancing current in the pot were also established.

As aluminum smelting technology has progressed, requirements for the rectifier equipment have changed as shown on Table 1.

The following characteristics are required of rectifier equipment for aluminum smelting.

### (1) Reliable power source

Because aluminum smelting uses the molten salt process, if the power source is shut down, molten

Fig.1 Current carrying test at the factory



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Table 1 Electrical requirements applicable to aluminum smelting

Year	1960s	→ After 1995
DC voltage	500 V	→ 1,200 to 1,500 V
DC current	50 to 120 kA	→ Approx. 340 kA or more
DC output capacity	25 to 60 MW	→ 400 to 510 MW

aluminum will coagulate. This will cause serious damage to the smelting facilities. High reliability is essential.

(2) 0 to 100 % wide-range voltage regulation

At the start of operation, 1 to 2 pot(s) will be energized, and thereafter 3 to 4 pots will be energized successively until all the pots have been energized. Therefore, wide-range voltage regulation is required.

(3) Automatic constant current control

The anode effect (AE), a phenomenon occurring in the molten salt process, has to be considered. When a shortage of raw material (alumina) occurs or the electrode (positive pole) wears away, gas is generated between the surfaces of the electrode and alumina, and the pot voltage is increased by 30 to 60 V. This means that the load resistance, as seen from the power source, becomes larger. If the output voltage of the rectifier equipment remains the same, the output current will be decreased. As a result, the production of the aluminum will be decreased. To prevent this, automatic control is required to keep the output current at the set value.

(4) High unit capacity

Normally, the smelting facilities will be provided with several rectifiers (4 to 5 units) to handle the rated DC output current. In addition, one rectifier unit will be always installed as a spare to insure the availability of DC power supply. High DC capacity rectifiers are required from the following reasons.

- ① To reduce the total power loss of rectifier equipment
- ② To reduce the space occupied by all the equipment, including equipment for the AC substation
- ③ To reduce the number of equipment that requires maintenance

(5) Digital control

The constant current control of the rectifier equipment will be implemented by PLC/HMI. Optimum control will be achieved by online control of the variables.

### 3. Transformer

To cope with the requirements for higher capacity rectifier equipment, many issues have to be resolved. Examples of some solutions achieved by Fuji Electric are listed below.

#### 3.1 Full-range on-load tap changer

As rectifier equipment ratings have increased, transformer unit ratings now range from 100 to 160 MVA. As mentioned before, the rectifier equipment for aluminum smelting requires a voltage adjustment range of 0 to 100 %. To comply with this requirement, the transformer has to be separated into a voltage regulating transformer and a rectifier transformer as shown in Fig. 2. Normally, this voltage

regulating transformer has a no-voltage tap changer (NVTC) with 3 to 4 taps and an on-load tap changer (OLTC) with about 33 taps. By combining the NVTC and OLTC, about 100 taps can be achieved. In this case, magnetizing inrush current of the voltage regulating transformer after the closing of the circuit breaker will include that portion due to the rectifier transformer. The magnetizing inrush current will be much larger than that of the regular transformer. This may cause a disturbance in the power supply system.

As a countermeasure, we decided to utilize an on-load tap changer with about 100 taps so that the output voltage can be adjusted simply by the OLTC. The full range of voltage can be adjusted without the use of the NVTC. When the circuit breaker is going to be closed, the lowest tap is set. Thus, the magnetizing inrush current was reduced substantially.

#### 3.2 Ideal twelve (12) pulse rectification

When large capacity rectifier equipment is used, 12-pulse rectification per unit is commonly applied. To minimize the harmonic current which flows into the power supply system, 4 to 5 units are connected together to configure a 48 to 60 pulse rectifying system per pot. In this case, if an unbalance (difference in no-load DC voltage and difference in short-circuit impedance) exists among the 6 pulse groups that comprise the 12-pulse rectification, the system will not be an ideal 12-pulse rectification system, and therefore, 5th and 7th harmonic current may flow into the power supply system. To prevent such unbalance, we adopted a two-tier core construction with an intermediate yoke.

Figure 3 shows a sketch of the core and winding configuration. The upper stage DC winding is connected in star configuration and in the lower stage DC winding is connected in delta configuration. Twelve-pulse rectification was realized with the single core construction. Naturally, there are an integer number of turns of the winding. Therefore, only an integer number of turns can be selected. For the rectifier transformer with high secondary current, a large number of turns cannot be selected. Therefore,

Fig.2 Simplified diagram of transformer-rectifier package

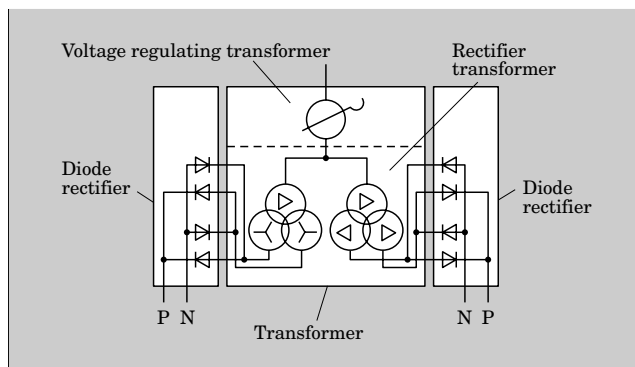
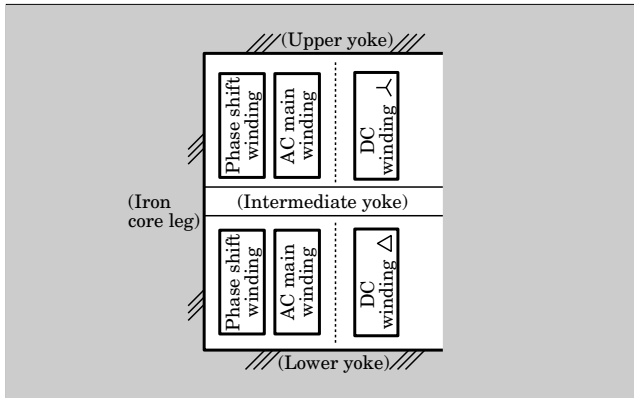


Fig.3 Cross section of the winding of a rectifier transformer



without an intermediate yoke, it is not possible to balance the no-load voltage between upper and lower stage windings. The ideal number of turns of the delta winding is  $\sqrt{3}$  times that of the star winding. But, this is not possible for the high current winding. For example, if we select 5 turns for the star winding, 9 turns would be the optimum number of turns for the delta winding. In this case, the no-load unbalance between both windings will be:

$$\left(\frac{9}{\sqrt{3} \times 5} - 1\right) \times 100 = 3.9 \%$$

Because the output DC circuit of both windings is common, this unbalance will be absorbed by VCR control. As a result of the unbalance, ideal 12-pulse rectification cannot be achieved. In the above case, 5th and 7th harmonic current which would be cancelled by real 12-pulse rectification will remain about 1 % of the fundamental current. In addition, the unbalance of the short-circuit impedance may increase the residual 5th and 7th harmonic current.

Our rectifier transformer is provided with an intermediate yoke and the differential flux between upper and lower windings can be bypassed. Therefore, the magnetic flux density of both winding can be selected individually. This means that the optimum number of turns can be selected for both DC windings. As a result, it is possible to limit the unbalance no-load voltage to within 0.2 %. In addition, because the dimensions of each winding stage can be selected individually, the short-circuit impedance of both windings can be balanced. Thus, we were able to realize a single core, space saving rectifier transformer with ideal 12-pulse rectification. By connecting 4 to 5 rectifier units, the merits of multiple rectification can be most efficiently utilized.

### 3.3 Internal construction of transformer

The main circuit configuration of the high capacity transformer for aluminum smelting usually comprises a voltage regulating transformer (single-winding transformer with full-range on-load tap changer) and a rectifier transformer for 12-pulse rectification (two-tier

construction with intermediate yoke and VCR). Because the rated secondary voltage of the voltage regulating transformer is the input voltage to the rectifier transformer, the manufacturer can select the secondary voltage arbitrarily and independent of the customer's requirements. If we select to increase the voltage, the current through the on-load tap changer may decrease, but the insulation level would be higher. We have to select the most suitable voltage considering these factors. The selection of the rated secondary voltage of the voltage regulating transformer is a key factor when planning the transformer design. Two factors were taken into consideration. First, the maximum voltage of the intermediate circuit during the tap changing process should not exceed the IEC specification of 72.5 kV. And secondly, the current through the on-load tap changer should be a value at which reliability of the on-load tap changer can be guaranteed. After due consideration, we selected 66 kV as the rated secondary voltage of the voltage regulating transformer.

When designing a high capacity transformer, transportation restrictions must also be considered. In our design, the voltage regulating transformer and the rectifier transformer are housed in separate tanks so that each transformer can be transported separately. In this case, both transformers will be installed side-by-side at the site and connected by an oil-filled duct. The insulation oil of the duct is completely separated from the oil of both transformers. The oil-filled duct is provided with its own conservator, pressure relief device, oil gauge, etc., to facilitate the maintenance work.

## 4. Diode Rectifier

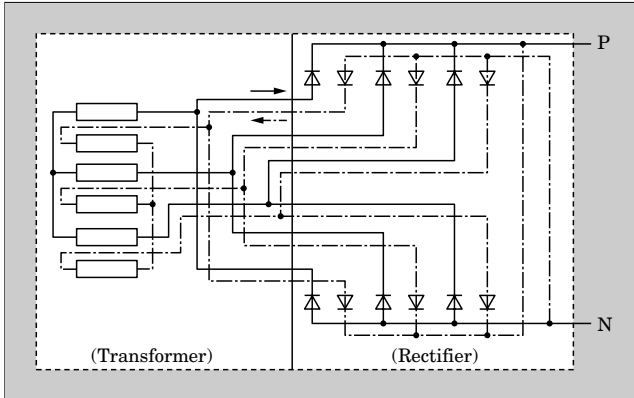
In the design of a high capacity rectifier, the following issues have to be resolved.

- (1) Measures to prevent local heating due to the high current
- (2) Awareness of the actual current unbalance between parallel connected elements
- (3) Application of technology to high capacity elements and their protection fuses
- (4) Measure to prevent the deterioration of high capacity fuses due to vibration

### 4.1 Measures to cope with local heating due to high current

Steel parts near the leads or terminals will become locally overheated due to the magnetic flux generated by the high AC current of the rectifier. Fuji Electric has for many years utilized an in-phase contra-polarity connection, which is very effective in preventing local heating due to a high current rectifier. The in-phase contra-polarity connection is a circuit configuration in which two groups of rectifier circuits with the same design are arranged so that the current of each group

Fig.4 Principle of in-phase contra-polarity connection



flows in opposite directions as shown in Fig. 4. Because the magnetic flux generated by one group will cancel the other, the parts or casing of the rectifier equipment will not overheat locally, even if those parts are made of steel. In addition, the in-phase contra-polarity connection exhibits the following advantageous characteristics for the design of rectifier equipment.

- (1) Because the inductance of transformer-rectifier connection leads and rectifier circuits can be greatly reduced, the voltage drop during the operation will be reduced and the power factor of the circuit will be improved.
- (2) Because the inductance of rectifier circuits can be greatly reduced, the current unbalance between elements will be improved.

#### 4.2 Current unbalance between diode elements

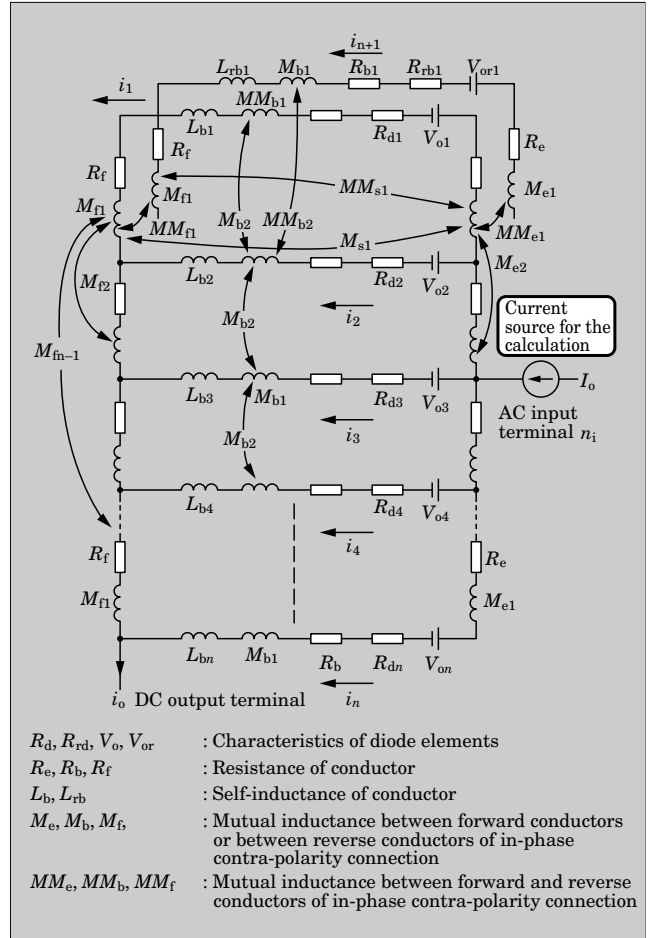
When several diode elements are connected in parallel, the current among each of the elements will not be uniform due to the different characteristics of the elements and the inductance of the conductor for each element. The required number of parallel elements will be determined based on consideration of the current unbalance. Reliability and economical efficiency will also be considered for this decision. Theoretically, the number of parallel elements can be calculated by the following formula, when one parallel redundancy is to be applied.

$$P = \frac{I_d \cdot \alpha}{K \cdot G \cdot I_s} + 1$$

- where,  $I_d$ : Rated output of the rectifier equipment  
 $\alpha$ : Current unbalance rate between the elements  
 $G$ : Number of sets of rectifier equipment  
 $I_s$ : Maximum available current per element  
 $K$ : 3 (for bridge connection)

The number of parallel elements is dependent on the current unbalance and the current unbalance is dependent on the inductance of the conductor for each

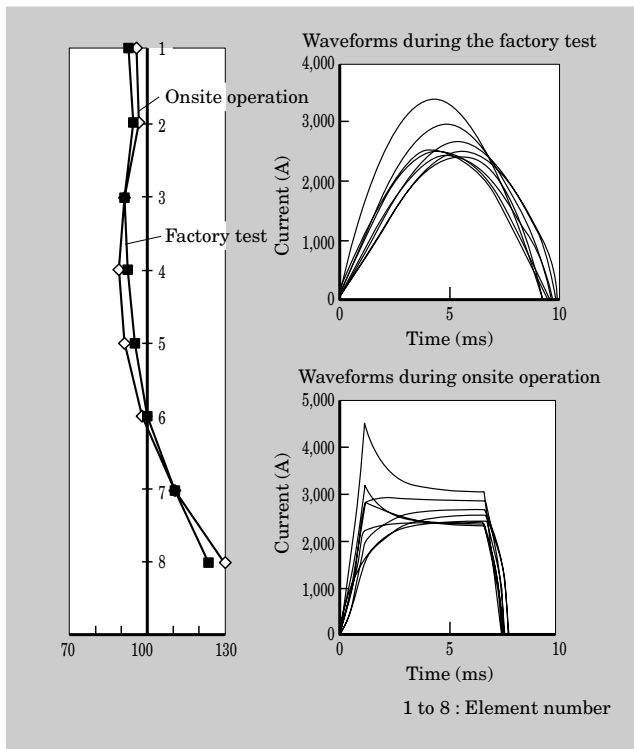
Fig.5 Simulation circuit of current unbalance



circuit and on the waveform of the current. At the factory, the current unbalance is measured by using the short-circuit method. Because the waveform of the current during the factory test is different from that during actual operation at the rated current, the actual current unbalance cannot be measured at the factory. But, it is important to know the actual current unbalance for the purpose of maintaining equipment reliability for long-term operation. Actual current unbalance can be measured by the simulation circuit shown in Fig. 5. By comparing the test data at the factory and the simulation circuit data, we are able to estimate the actual current unbalance at the rated current.

Figure 5 shows an example of the equivalent circuit for simulating the parallel element peripheral circuitry. Because two groups of rectifiers are connected in an in-phase contra-polarity connection, two groups of rectifier have to be simulated at the same time. Also, mutual inductance between several conductors must be simulated in detail. The current through each path can be calculated using general-purpose circuit analysis software. Figure 6 is an example of the results of simulation, and shows the current waveforms of each current path under factory test conditions and during actual operation at the rated output and also shows

Fig.6 Example of the result of current unbalance simulation



the current unbalance at that time. This example simulation is for the case of 8 parallel elements. The horizontal axis of the graph shows the percentage of current flowing through each element, assuming that the average current is 100 %. Because the factory test is performed by the short-circuit method, the waveform of current flowing through each path will be almost sinusoidal. However, the waveform of the current during actual operation will be almost a square wave. Because the current unbalance is affected by the inductance, it may also be affected by the difference in waveforms of the current. From the results of the simulation, we can estimate the difference of the unbalance quantitatively.

#### 4.3 Technology applied to high capacity diode elements and protection fuses

The high-withstand-voltage/high-current flat-type diode was developed to realize high capacity rectifier equipment. Table 2 lists the major characteristics of the developed diode and Fig. 7 shows its appearance.

The newly developed diode has a pole diameter of 80 mm, a pellet diameter of 89 mm, and its rated voltage and current are 4,500 V and 3,000 A, respectively. In addition, Fuji Electric also provides a series of diodes rated at 5,000 V. For the development of the new diode, several modern technologies were adopted. Below, some of those new technologies are introduced.

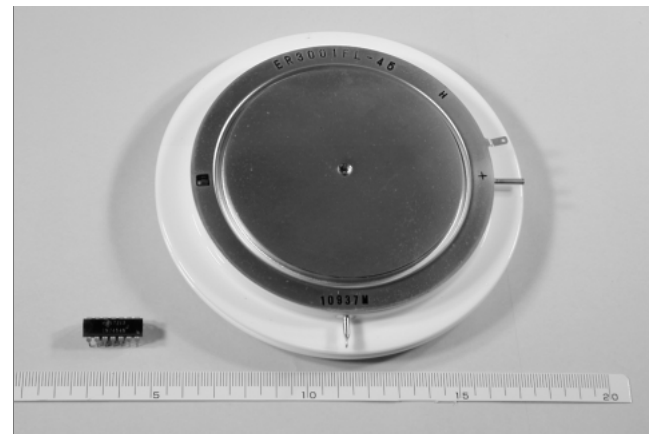
##### (1) Establishment of uniform diffusion technology

To ensure the uniform diffusion layer and surface density of large diameter silicone plates, we developed a custom silicone wafer in collaboration with a silicone

Table 2 Summary of the high-voltage high-current flat-type diode

Description	Symbol	Type of diode	Unit
		ER3001FL-45	
Repetitive reverse voltage	$V_{RRM}$	4,500	V
Non-repetitive reverse voltage	$V_{RSM}$	4,700	V
Mean forward current	$I_{F(AV)}$	3,000 ( $T_f = 80^\circ\text{C}$ )	A
Surge forward current (with reverse voltage)	$I_{FSM}$	58,000	A
Junction temperature	$T_j$	- 40 to +160	$^\circ\text{C}$
Forward voltage	$V_{FM}$	1.65	V
Reverse current	$I_{RRM}$	300	mA
Heat resistance	$R_{th(j-f)}$	0.013	k/W

Fig.7 New flat-type diode element (ER3001FL-45)



wafer manufacturer. Utilizing this new silicone wafer, we succeeded in reducing the non-uniformity of diode characteristics to 50 % of the conventional type.

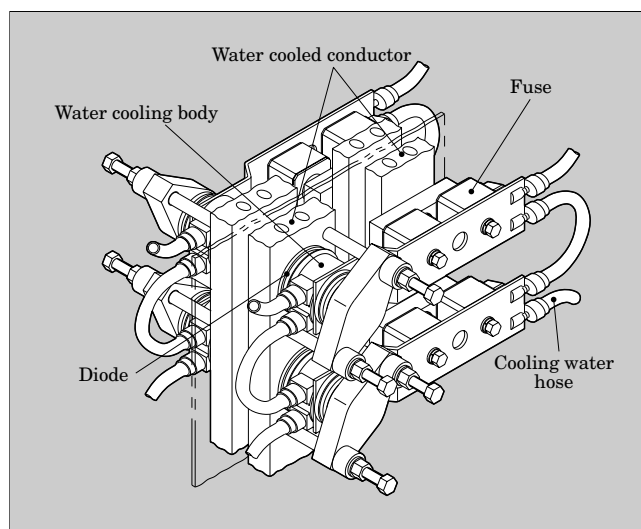
##### (2) Realization of higher voltage diode

To improve the withstand-voltage of the diode, it is essential that the voltage distribution in the diode be understood in order to determine its internal construction and insulation material. We simulated the voltage distribution in the diode and verified how the voltage distribution would be affected by changing the shape of internal parts. Based on the results of simulation, we designed the package internal construction for high reliability. In addition, tetra fluoride ethylene resin insulation parts made by a mechanical cutting process were replaced by polyimide resin molded insulation parts. This contributed to the reduced cost of the diode.

To select fuses for equipment and semiconductor protection, we need to know the exact rating of the surge forward current of diode. We verified the diode endurance by causing an actual current to flow with reverse voltage using the short-circuit generator (2,000 MVA) at our high-voltage and high-power testing laboratory.

With the increasing current ratings of diodes, higher current semiconductor protection fuses are

Fig.8 Sketch of the stack



required. Fuses used for MOZAL were rated at 4,000 A and 1,350 V. Those fuses were a twin-type consisting of two parallel fuses with external dimensions of 105 mm-by-105 mm and total weight of about 9 kg. Recently, a press-pack design in which a fuse and a diode are pressed together is adopted in some applications for high current diode/fuse combinations. In such a design, if the fuse is blown, both the fuse and diode must be disassembled, and thus this design is undesirable for maintenance work. Therefore, Fuji Electric decided to follow the traditional method of fuse

and diode installation. However, we had to resolve a problem regarding the rigidity of the conductor that connects the fuse and diode.

When a fuse and diode are installed separately, a conductor to connect them is required. To limit the mechanical force applied to the fuse, the thickness of the conductor has to be limited. But, this means that current carrying capacity of the conductor would be limited and would be insufficient for a high current diode and fuse.

To solve this problem, we developed a conductor having a thickness of 5 mm and provided with a path for cooling water. Thus, a high-current connecting conductor with low rigidity was made possible. Fuses can be cooled from both sides by water and sufficient current capacity is achieved. Figure 8 shows a sketch of this stack.

## 5. Conclusion

The demand for aluminum is increasing from year to year. Therefore, investment in aluminum smelting equipment will definitely continue. Fuji Electric has supplied 34 units (including units currently being manufactured) of rectifier equipment to seven plants in the past five years. We will continue to make an effort to realize more economical and more reliable rectifier equipment, and hope to be able to contribute to the aluminum industry.



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