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FREON COOLED SILICON RECTIFIER EQUIPMENT

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I. INTRODUCTION

In silicon rectifier cells, there is a heat loss of several hundred watts per cm^2 of the electrode surface, and therefore cell cooling is a very important factor in respect to the current capacity of the cell. Previously, air or transformer oil was generally used as the cell coolant. However, as equipment has increased in capacity but tended to become more compact, these coolants proved to be limited in their cooling capacity. In the equipment described in this article, Freon was employed as the coolant. This was the first time that semiconductor rectifier equipment had been manufactured in Japan incorporating this new highly effective cooling system utilizing the boiling heat transfer of Freon. The equipment was delivered to the Shinkosha K.K. in August, 1968 as a power source for water electrolysis, and so far performance has been highly satisfactory. This article will give an outline of this equipment.

II. CELL COOLING USING BOILING FREON

The current capacity in semiconductor rectifier equipment is decided mainly according to the amount of heat loss at the permissible cell junction temperature. The permissible cell junction temperature is an inherent property of the individual cell unit, but if the coolant thermal resistance is small, only a corresponding amount of heat will be lost and therefore the current load capacity can be increased. This relation is shown by the following equation.

$$P = \Delta T/(R_{jc}+R_{ca}) \quad \cdots\cdots (1)$$

where P : permissible heat loss (w)

ΔT: temperature difference between permissible cell junction temperature and the final medium, i.e. the surrounding air (deg.)

R_{jc} : thermal resistance between cell case and cell junction, i.e. thermal resistance of cell interior (deg/w)

R_{ca} : thermal resistance between cell case and final medium, i.e. thermal resistance of coolant (deg/w)

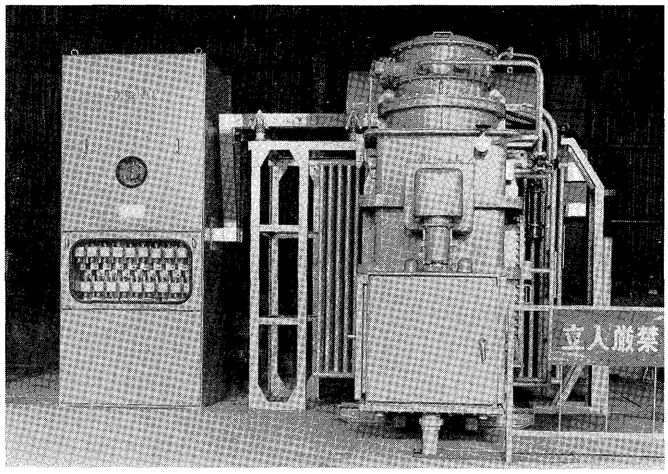


Fig. 1 The rectifier equipment (left) under operation

The thermal resistance of the coolant R_{ca} in former cooling methods such as the oil cooling system was several times larger than the thermal resistance of the cell interior, R_{jc}. However in this Freon cooled equipment, the R_{jc} and R_{ca} values are almost the same.

Since the semiconductor cells are immersed in Freon liquid in a sealed vessel, the heat generated from the cell is absorbed by the boiling liquid Freon in contact with the cell case surface or the cooling electrode touching the cell. When the Freon vapor condenses on the vessel walls, the heat is radiated to the exterior and forced air cooling is carried out on the exterior surface of the vessel. The heat transfer coefficient of boiling Freon is extremely high; experiments give values of 2000～7000 kcal/m^2·hr·deg. which is about ten times that of oil. The relation between the difference between liquid temperature and the temperature of the heat transfer surface for boiling heat transfer, ΔT_{sat}, and the heat flux·q (amount of heat per unit area per unit time) is as follows.

$$\Delta T_{sat} \propto q^{1/m} \quad \cdots\cdots (2)$$

For Freon liquid, the value of the index number m is approximately 6. In usual convection heat transfer, m is 1 and the temperature difference ΔT_{sat} increases proportionally as the heat flux q increases. With boiling convection, however, ΔT_{sat} obviously does not increase relative to increases in q. Because of this property, the boiling convection of Freon is much better than that of previous methods such as the oil cooling.

The heat transfer coefficient when the Freon vapor condenses is about 1500 kcal/m^2·hr·deg, which is about 3 times that with transformer oil forced convection.

As mentioned above, the basic point of this equipment is clearly that R_{jc} is much lower than with previous systems.

When Freon liquid is in the boiling state, a large number of bubble nuclei form on the surface of the cooling electrodes and cell case. These nuclei gradually enlarge until they form air bubbles. When they reach a certain size depending on the heat flux, they separate from the heating surface, cause strong agitation in the liquid and eventually rise to the liquid surface. The air bubble nuclei generation density (number generated per unit surface area) and generation cycle (number generated per unit time) both increase in accordance with the magnitude of the heat flux. Therefore, the nearer the cells (which are a source of heat), the greater the generation of air bubbles, the more rapidly they rise and the more violent the agitation.

Since the Freon is in direct contact with the cells, a very high dielectric strength is required. The Freon breakdown voltage is lowest at temperatures of around 20°C but even then the value is about 20 kv/mm which is the same as that of transformer oil. This is a favorable characteristic in respect to the compact electrodes and the small cell gap.

III. OUTLINE OF THE EQUIPMENT

Fig. 2 is a connection diagram of the main circuits in this equipment. The dc voltage can be continuously adjusted between dc 460~600 v by means of a voltage control reactor (dc 38 v, control possible) or an on-load tap changer for the rectifier transformer. With this dc voltage, constant current automatic control can be carried out by regulating the current of the dc control winding of the voltage control reactor. The protective system consists of 2 parallel connected super rapid fuses inserted in series with each rectifier cell. In case the semiconductors breakdown, the fuses burn out and the defective semiconductor is cut off from the circuit. When the dc current is too large, the instantaneous over-current relay in the ac side of the rectifier-transformer and the induction-type over-current relay on the dc side open the circuit breakers on the ac and dc sides respectively. In order to prevent the overcurrent which arises in the electrolysis cell characteristics during starting, the starting current is limited up to the decomposition voltage of the cell by means of a starting resistance.

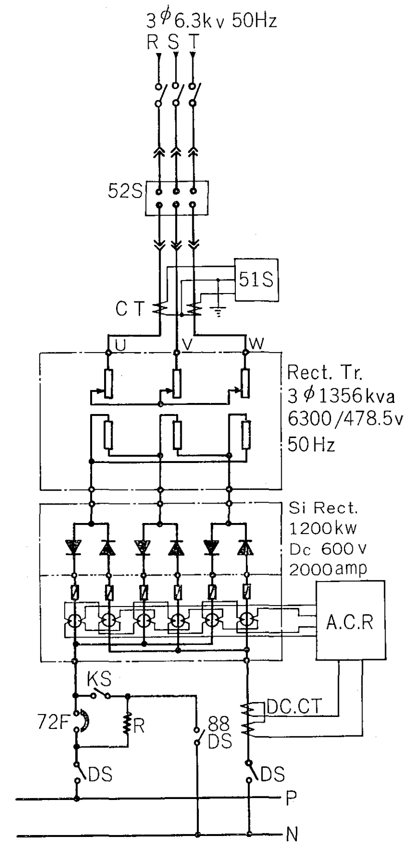


Fig. 2 Connection diagram of main circuit

IV. SPECIFICATIONS OF THE RECTIFIER EQUIPMENT

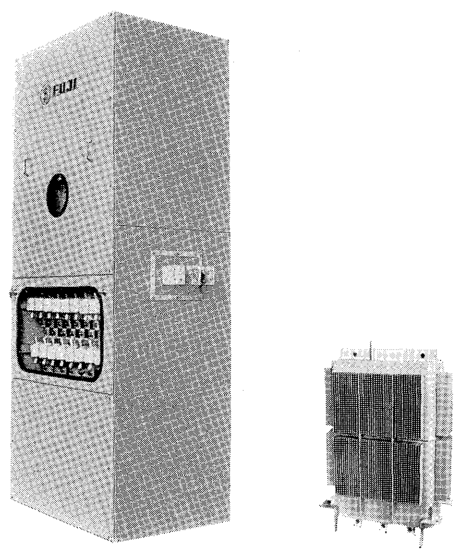
The specifications of the rectifier equipment delivered to Shinkosha K.K. are as follows.

Rated dc voltage :	600 v
Rated dc current :	2000 amp
Rated dc output :	1200 kw
Type of rating :	A_0 (continuous rating)
Rated frequency :	50 Hz
Standard :	JEM 1156
Connection :	2-phase bridge connection
Cell :	disc-type cell KSN 01–16
Components :	No. of series cells 1 No. of parallel cells 3 Even if one of the 3 parallel cells is defective, operation can be continued without any decrease in the ratings.
Protective fuses :	RF 1233 f–350 B Two fuses connected in parallel are used for each cell
Cell cooling system :	Freon cooling
Equipment cooling system :	Forced air cooling
Internal components :	Voltage control reactor Air flow relay Dial thermometer Cooling fan

V. CONSTRUCTION OF RECTIFIER EQUIPMENT

An outer view of the rectifier equipment is shown in *Fig. 3*. This equipment is in a cubicle which contains the rectifier unit, protective fuses, voltage control reactor, cooling fan, air flow relay and dial thermometer. The construction of this cubicle is shown in *Fig. 4*.

The rectifier units consist of 2 groups arranged one behind the other. They can be removed from either the front or back of the cubicle by taking off the cover plate. Below each rectifier unit, 2 super rapid fuses per cell are arranged one behind the other like the rectifier units. The fuses can be easily replaced by removing the fuse inspection windows on the front and back. Below the fuses, there are 6 voltage control reactors whose control windings are supplied with control current from the panel exterior.



(a) (b)

Fig. 3 Outer view of rectifier cubicle and rectifier unit

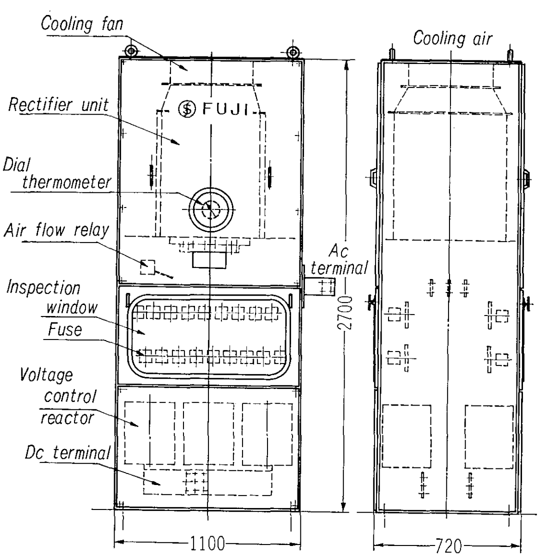


Fig. 4 Construction of rectifier cubicle

Cooling air is brought in through the lower part of the cubicle and after cooling the voltage control reactors, fuses and rectifier units, it is exhausted upwards by the cooling fan located in the top of the cublicle. The temperature of the cooling air at the outlet is monitored by the dial thermometer and any stoppage of the air flow caused by a breakdown of the cooling fan is monitored by the air flow relay. In case there should be an accident, the ac circuit breaker opens so as to protect the rectifier units. The ac bus terminal projects from the side of the cubicle to make it easy to connect with the adjacent rectifier transformer. The dc bus is connected to the exterior via the buttom surface of the cubicle.

VI. RECTIFIER UNIT CONSTRUCTION

An external view of the rectifier unit is shown in *Fig. 3 (b)*, while the interior construction is shown in *Fig. 5*. The rectifier unit consists of a sealed vessel, rectifier stack, Freon liquid and terminals.

1. Sealed Vessel

This vessel is of sealed construction and made of iron, with no packings anywhere. Several aluminum fins are soldered to the interior of the vessel. These fins provide the required surface for Freon vapor condensation. In the upper part of the vessel, there is a space for the formation of Freon vapor. The external fins provide the surface area required for the dispersion of heat loss from the interior.

If there is any air remaining in the vessel, it becomes difficult to get the Freon to boil and water particles in the air will increase the possibility of corrosion. For these reasons, it is necessary to create a vacuum in the sealed vessel. During the manufacturing process, all leakages are kept to below $1 \times 10^{-6} \mu Hg \cdot l/sec$ using a helium leak detector. Thermal gas removal treatment is also carried out to eliminate any gas adhering to the interior of the vessel. The

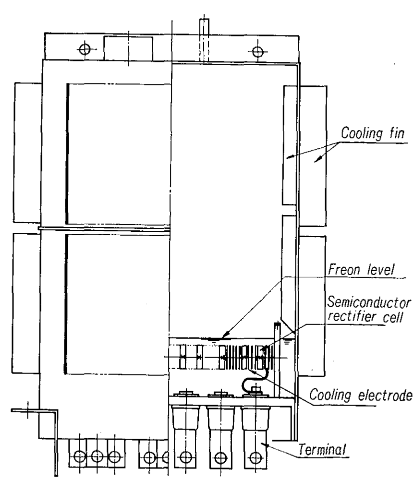


Fig. 5 Sectional view of silicon rectifier unit

pressure inside the vessel during use is at the most $1\ kg/cm^2$ atg (equivalent to the saturated vapor pressure of liquid Freon at 70°C), but this is of no importance since the vessel has a breaking strength of $10\ kg/cm^2$ atg. For safety, a buffer plate which moves at $7\ kg/cm^2$ atg is soldered to the vessel so that no air leaks occur even with repeated pressures.

2. Rectifier Stack

The 9 rectifier cells for 3 arms are combined in a single-shaft rectifier stack which includes the cooling electrodes and insulators. The cells are clamped together under pressure of 300 kg by means of 3 studs via plate springs at one end. The cooling electrodes serve both as cooling fins which provide the required surface area for dissipation of the heat which occurs when the Freon boils due the heat from the cells, as well as means for pulling out the conductors. A flexible lead wire is used when removing the conductors. An outer view of the rectifier stack is shown in *Fig. 6*.

3. Terminals

The terminals are made of epoxy resin and can be used without damage under repeated application of heat. As shown in *Fig. 7*, all 12 terminals are in the form of a single casting which underwent a leak test using the same type of helium leak detector as with the vessel. The leaks are limited to below $1 \times 10^{-6}\ \mu Hg \cdot l/sec$.

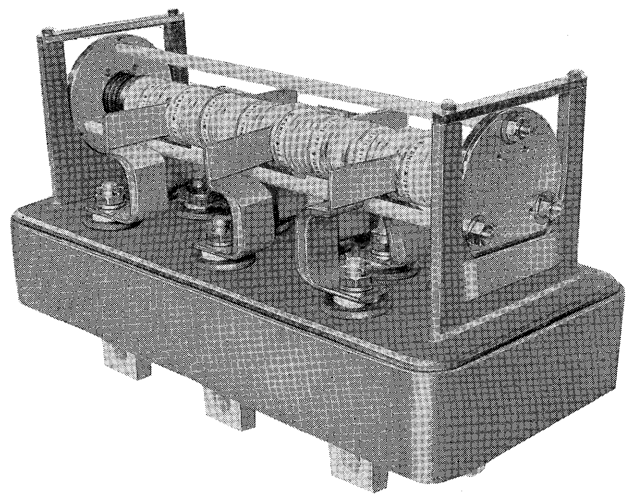


Fig. 6 Outer view of rectifier stack

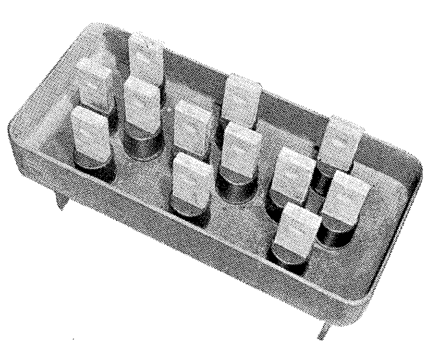


Fig. 7 Outer view of epoxy resin terminal

4. Freon Liquid

The Freon was introduced into the vessel under vacuum and the filling process carried out so that no air will enter the vessel. After the Freon was introduced into the vessel, the exhaust pipe was completely sealed off to prevent the entry of outside air.

During operation, the boiling Freon on the cell case surface and on the cooling electrodes which contact this surface inside the unit vaporizes, rises upwards in the vessel, comes into contact with the cooling fins on the inner surface of the vessel, condenses and thus gives heat to the vessel wall. The condensed liquid Freon again returns to the bottom part of the vessel in the form of droplets. In this way the boiling/condensation cycle repeats itself.

VII. FEATURES

This equipment exhibits the following features.

1) Since cooling is carried out by utilizing boiling heat transfer of Freon in direct contact with the cells, the cooling efficiency is much better than that of usual systems, while the number of semiconductors is only about 1/2 that of former systems. The rectifier equipment is therefore very compact.

2) Since the coolant is circulated in a boiling/condensation cycle, no movable coolant circulation parts are required.

3) Since the rectifier equipment is constructed of units with appropriate capacities, it can be adapted for any capacity and assembly or disassembly is simple.

4) Since the rectifier units are of welded, sealed construction, they can be used almost indefinitely without any leakages of Freon vapor.

5) The rectifier units are constructed of materials which are corrosion resistant to Freon.

VIII. RESULTS OF TEMPERATURE RISE TEST ON THE RECTIFIER UNITS

The results of temperature rise tests conducted on the equipment delivered to Shinkosha K.K. are shown in *Fig. 8*. For these tests, one cell was connected in series and two cells were connected in parallel, temperature rises in respect to a dc current were measured in various places. For the rated current, the temperature rise of the cell junction in respect to the input air temperature was the largest at 65°C, while the rise in the Freon liquid was 15°C. For this reason, there is a sufficiently large margin in the cell junction and the cell current capacity has been increased to about twice that of previous types. *Fig. 9* shows the variation of the total thermal re-

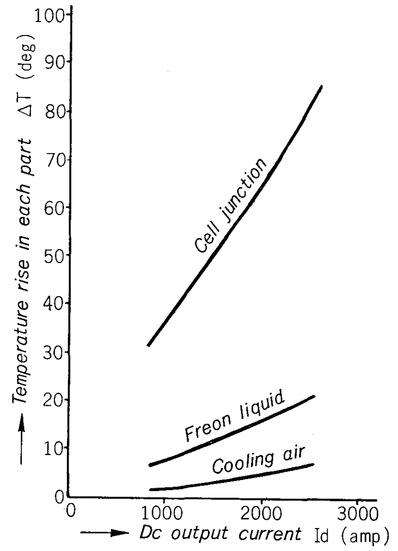


Fig. 8 **Temperature rise characteristics of the rectifier unit**

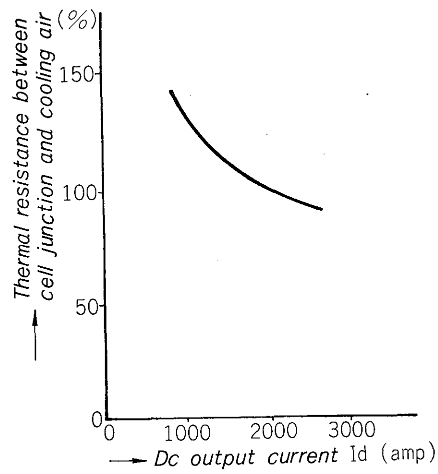


Fig. 9 **Characteristics of thermal resistance between cell junction and cooling air**

sistance (between cell junction and cooling air) in respect to dc current. This total thermal resistance is obtained from the cell junction temperature rise and the amount of cooling. The relation of the boiling heat transfer thermal resistance to increases and decreases in the heat flux is also evident from *Fig. 9.*

IX. CONCLUSION

This article has described the various merits of semiconductor rectifier equipment employing boiling Freon for cooling. As semiconductor rectifier equipment continues to increase in capacity, and the current capacity of the cell rise accordingly, there will be greater need for more compact equipment and a reduction in the number of current balance devices. Since Freon cooled semiconductor rectifier equipment meets all these requirements, it will no doubt become much more popular in the future.