PROGRESS IN PUMPLESS MERCURY-ARC RECTIFIERS

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I. INTRODUCTION

In Japan, the effort to manufacture the steel-tank pumpless mercury-arc rectifier had been started since about 1940. Several years ago this scheme was accomplished.

The first pumpless rectifier set put into actual service in Japan was the vessel delivered to Keio-Teito Electric Railway Co. from our works in 1953, rated 1,500 V 1,000 kW in heavy nominal rating. Since then many pumpless rectifiers have been put into service not only in electrical railway substations, but also as direct current sources and as speed control devices of motors in many factories in all fields of industry. I will introduce below the recent state of developments in pumpless rectifier manufacturing.

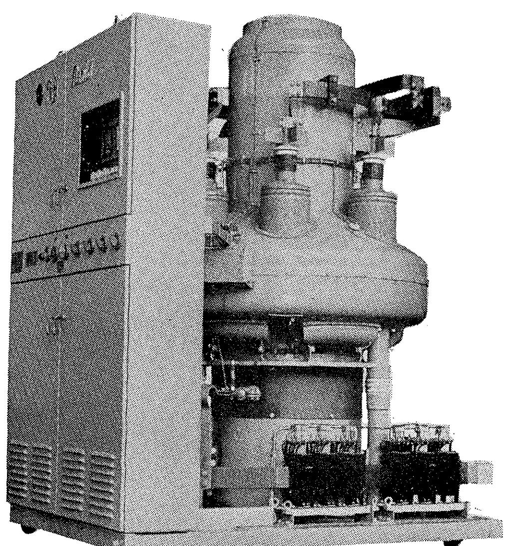
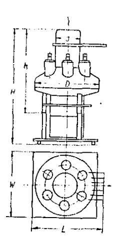


Fig. 1. Air-cooled multi-anode pumpless rectifier, type PSL2011, 1,500 V/600 V 2,000/2,500 A

II. DEVELOPMENT OF STANDARD TYPES OF PUMPLESS RECTIFIERS

We have, as products of our works, four standard types of pumpless rectifiers as listed in Table 1. They are air-cooled and of 6-anode type. I think, PSL2011 is the largest type among multi-anode type pumpless rectifiers in the world. The reasons on which we adopted the air-cooled and 6-anode type in the standard series of pumpless vessels are as follows :

Table 1. Standard types of air-cooled multi-anode pumpless rectifiers

			PSL 0311	PSL 0611	PSL 1211	PSL 2011
Capacity	Voltage (V)		1,500/600	1,500/600	1,500/600	1,500/600
	Current (A)		350	700	1,250	2,000/2,500
	Output (kW) (Nominal or heavy nominal)		300/125	500/250	1,000/500	2,000/1,000
Dimension (mm)		D	720	1,015	1,235	1,535
		d	320	460	595	690
		h	1,100	1,590	1,870	2,085
		W	1,000	1,100	1,420	1,700
		L	1,000	1,100	1,420	1,700
		H	1,770	2,170	2,545	2,825
Floor space (m^3)			1.0	1.21	2.02	2.89
Weight	Vessel (kg)		350	500	750	1,300
	Total		450	750	1,100	2,000
Output of cooling fan (IP)		50∿	¼	½	1.5	1.5
		60∿	¼	¾	1.5	1.5
Air quantity needed (m^3/s)		50∿	0.35	0.65	1.4	1.5
		60∿	0.4	0.75	1.6	1.65

Air-cooled or water cooled ; It is a common idea in machine design to prefer the water-cooled construction rather than the air-cooled above a certain output, due to small dimensions, weight and manufacturing costs. But in rectifier design, there are a few special aspects. The problem of electric corrosion in vacuum tank wall leads to use a recooler system. Further more, in pumpless rectifier construction, we can not disregard the diffusion of hydrogen gas in steel wall when it is water-cooled. Therefore the superiority of the water-cooled construction is not always remarkable even in large vessel design. I think the air-cooled type is more economical than the water-cooled in case of the output of our type PSL2011, i.e. 600 V 2,500 A or 1,500 V 2,000 A. Moreover, the people on user side complain on the troubles in water cooling system from view of maintenance. From these points our Company decided to adopt the air-cooled construction in the standard series of pumpless rectifiers.

Single-anode or multi-anode; We had abundant experiences in our works in manufacturing multi-anode type rectifiers and also single-anode type rectifiers in pumped rectifier age. Advocates of single-anode rectifier maintain the smaller arc-drop and convenience in spare vessels of the single-anode type. Principally the single-anode type has smaller arc-drop due to the short distance between anode and cathode on one side, but on the other side, as illustrated in Fig. 2, mercury vapour stream from

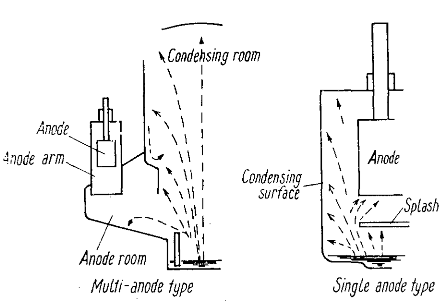
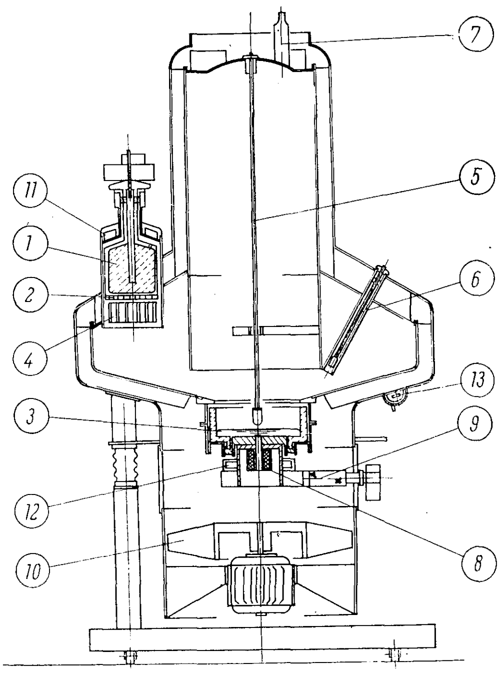


Fig. 2. Comparison of rectifier construction

cathode can easily approach the anode in the single-anode construction and disturbs the vapour density conditions in the surroundings of anode which influence the endurance against back-fire. To prevent this trend to arc-back, splash baffle and narrow deionization baffle are inserted in arc path in practical design and as a result of these, arc-drops become nearly equal in both types of rectifier, single-anode type and multi-anode type. In the view point of spare vessels, the single-anode type is more convenient than the multi-anode one. On the other hand, the multi-anode type has a remarkable feature of simpleness in manufacturing and also in maintenance in auxiliary equipments, i.e. ignition and excitation device, cooling and temperature controlling system and so on due to the single vacuum vessel. Considering these merits and demerits of both types, we chose the 6-anode type construction as a series of standard pumpless rectifiers. Among multi-anode constructions, 12-anodic and 18-anodic vessels were manufactured formerly for large output rectifiers. But these types have comparatively large values of arc-drop due to the large diameter of vacuum tank. We studied in many years to raise the current value per one anode and accomplished the type PSL 2011 of 6-anode construction and having a current output of 2,500 A. We have made exhaustive researches strenuously in the improvement of cooling construction of vacuum vessel. In the view-point of cooling, the separation of anode-room and mercury vapour condensing dome in multi-anodic construction presents a suitable form for vessel cooling and enables to hold a comparatively low vapour density in surroundings of anode and grid which influences the arc-back resistivity and other electrical properties. In Fig. 3, principal construction of the type PSL 2011 is illustrated by a sectional drawing.



1. Main Anode
2. Grid
3. Cathode
4. Baffle
5. Ignition anode
6. Excitation anode
7. Sealed off pumping tube
8. Ignition solenoid
9. Cathode lead
10. Cooling fan
11. Anode heater
12. Cathode heater
13. Vessel heater

Fig. 3. Schematic construction

III. CONSTRUCTION DETAILS AND MANUFACTURING TECHNICS

There are several important points in the manufature of pumpless mercury-arc rectifier. The first of them is to accomplish a perfect vacuum tightness of vessels, i.e. suitable construction of insulating vacuum seal at the stems of many electrodes and its fabrications, precise detection of vacuum leak at vessel walls and welded lines, etc. The second is the perfect degassing of the materials employed to build the vacuum vessel, including the selection of various materials, for instance, electrode graphite, steel plates for vessel construction, mercury and so on.

Insulating seal of electrodes; There are several methods as illustrated in Fig. 4 in insulating

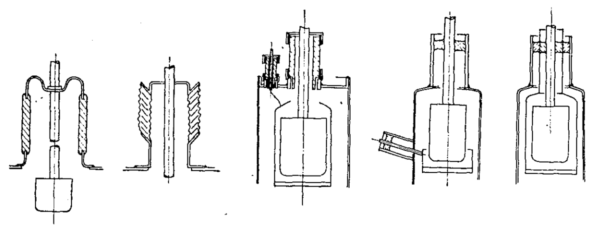


Fig. 4. Compositions of anode seal

vacuum seal of electrode conductor applied to recent steel-tank pumpless rectifier constructions. (a) is the so-called matched sealing method in which seal glass and the both metals to be fixed together by seal glass are arranged to have equal thermal expansion coefficients in service temperature region. In (b) several thin plates of metal are fixed together by intermediate glass enamel and the internal stress due to thermal expansion is distributed to these glass enamel layers. In case of (c) the metals are sealed on insulating porcelain by hard or soft soldering and the expansion stress is borne by soldering layer. Our Company uses the methods (d) and (e). There are primarily two methods, matched system, and unmatched system, in glass sealing technics. In the matched system as (a) the stress due to thermal expansion is transferred to the strain in metal thin plate, but frequently tensile force trends to affect on seal glass. As is well-known, the glass is ten times stronger against compressive stress compared to the durability to tensile stress. The method (d) and (e) are the unmatched system in which seal glass and the both metals to be fixed to it are arranged deliberately to have slightly different values of thermal expansion coefficent as shown in Fig. 5 and sealed together in fused condition of glass in high temperature. In this construction, the stress raised in glass in the normal operating temperature is always compressive

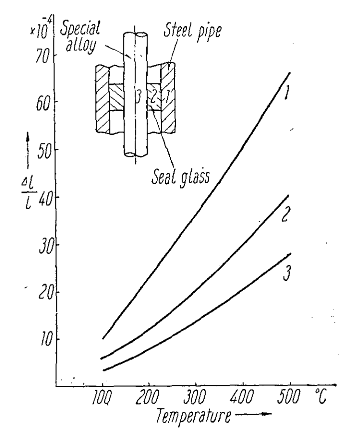
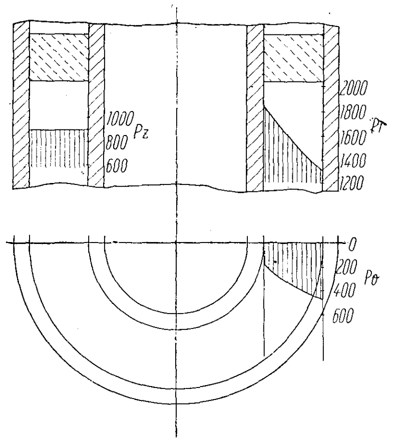


Fig. 5. Thermal expansion characteristics of sealing materials



Compression stress (kg/cm²) {in radial direction, P_r; in tangential direction, P_θ; in axial stress P_z}

Fig. 6. Distribution of internal stresses

as illustrated in Fig. 6. As the result of our tremendous research based on several hundred trials, we attained to get the ideal combination of materials in which the stresses in all directions are compressive. The photograph in Fig. 7 is a result of photo-elastic testing. This construction has also a a merit to be produced by comparatively easy process. Each product is thrown into the testing process in which rapid heating and cooling cycle

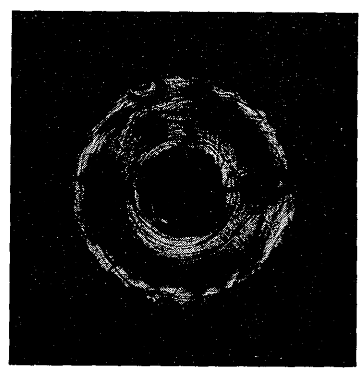


Fig. 7. Result of photo-elasticity-test for glass-seal construction

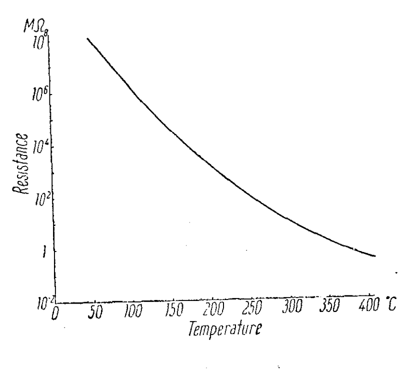


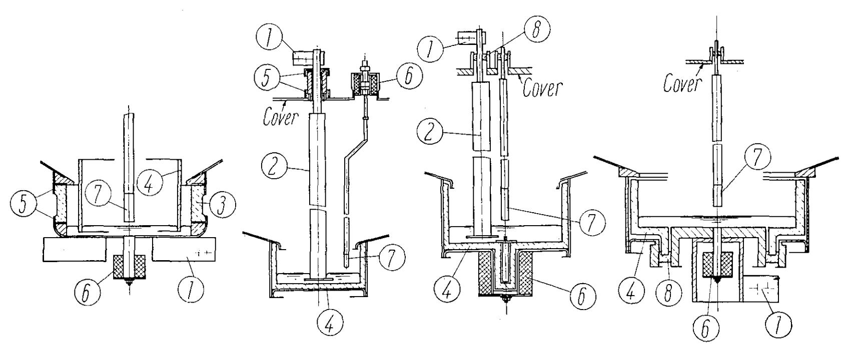
Fig. 8. Temperature characteristics in insulation resistance of seal-glass

between room temperature and 300°C is repeated five times in every 30 minutes and after this, leakage test is carried out. Short circuit current tests were practised several ten times for picked up samples and the results of this test proved the excellent durability of the unmatched system against the impact thermal stress. The adhesion strength between glass and metals exceeds 300 kg/cm^2 and the shearing strength of seal glass is ca 500 kg/cm^2, consequently the sealing construction as a whole bears easily several tons axial load. The insulating resistance characteristics of glass in some temperature extent is excellent as shown in Fig. 8. The puncture voltage stress of seal glass is 20 kV/mm and the surface flash-over voltage presents a value of 6.5 kV/cm.

Cathode and ignition device construction ; Several different methods as shown in Fig. 9 are applied to the cathode and ignition device constructions in modern steel-tank pumpless rectifiers. (a) can be considered as an extension of the pumped rectifier cathode in which the cathode insulator is sealed to the vessel and cathode bottom plate by hard or soft soldering. In the construction of (b), cathode mercury is pooled in a quartz bowl and from there the cathode conductor is led passing uprightly through vacuum tank to the vessel cover and sealed there vacuum-tightly to the cover. In this case as a shifting device of the ignition anode, ignition solenoid on the cover and a spring under it are arranged near the fixing point of ignition pole-lead. The methods we are using are (c) and (d). In smaller output vessels under PSL2011 among our standard vessels, the method (c) is now applied. This method is similar to (b), but instead of moving the ignition pole, a jet of mercury is shot from cathode mercury surface to the ignition anode head by a solenoid prepared surrounding the the pipe-shaped projected part of cathode quartz bowl bottom. We chose this construction instead of (b) considering two technical points ; In the first, the shifting motion of the ignition pole up and down trends to cause breakage or falling off of ignition head. Next, a spring inserted in the vacuum tank is feared to yield during the high temperature heat-treatment of vacuum vessel. In the construction of the largest type PSL2011, we adopted the method (d). The system (c) presents two demerits in case of large capacity vessels ; One is the increase of diameter and weight of the steel cathode rod and the other is the elongation of this rod due to the high temperature in operating conditions, which necessitates to deepen the mercury pool. In the construction (d), the insulating seal of the cathode lead is brought to the bottom and a quartz funnel as mercury container is adhered to seal glass of this part. By the development of this construction, carrying out the cathode current of 3,000 A and above became able to practise with no fear.

Construction of cooling surface on vessel ; In the design of air-cooled rectifier, it is essential to minimize the vacuum vessel dimensions by raising the heat transfer quantity per unit area of the cooling surface. Based on the fact that the heat transfer rate of the air-cooled surface is remarkably raised by occurrance of eddy flow, we planted many short copper fins bended zigzag alternatively on all cooling surface of vacuum vessel. This method obtained the expected results and enabled us to construct fairly small vessels for output current of 2,000 to 2,500 A.

Leak detection ; Leak through the vessel wall into the vacuum tank is fatal for pumpless rectifier. It is essential to take plenty of care to the selection of steel plates and other materials to be used for vacuum tank wall and welding process of them. Generally, most of gases do not permeate through steel plate, but hydrogen does a little. (see Fig. 12)



1. Cathode terminal
2. Cathode lead
3. Cathode insulator
4. Cathode quarts
5. Soldering (soft or hard)
6. Ignition solenoid
7. Ignition anode
8. Glass seal

Fig. 9. Constructions of cathode and igniting device

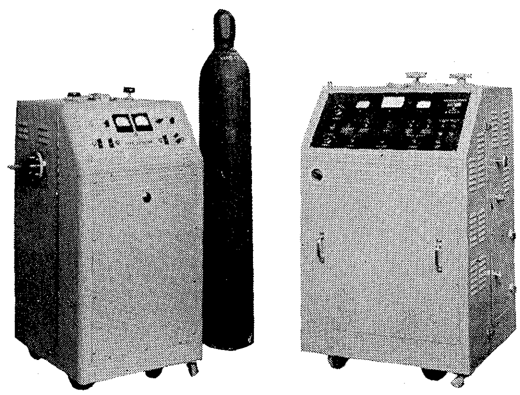


Fig. 10. Helium leak dectors
(Left: CEC-made, Right: Shimazu-made)

But considering the rarity of hydrogen in the atmosphere, permeation through the steel plate itself needs no attention in practical cases when the air-cooled system is employed for cooling. But easiness of welding work is important and from this point of view we use special mild steel of few carbon content as vessel wall material. To build the water-cooled rectifier vessels, stainless steel or steel plate soldered with copper cooling pipes are used.

Leak detecting method to examine the quality of manufacturing work should have precise accuracy in detecting leakage rate which satisfy the needs of pumpless rectifier vessels and further-more must have characteristics suitable for workshop application. I think the most advanced leak detecting method to-day is the helium detector based on the principle of massspectroscope which was developed in America since the last war. We, in our works, are using two measuring instruments of this kind for making pumpless rectifiers, one is made by C.E.C. Co. in America and presents an detecting accuracy of 7.6×10^{-7} μHg-l/s and another is made by Shimazu Mfg. Co. in Kyoto. (Fig. 10) The principle of leak detection with these helium detectors is illustrated in Fig. 11.

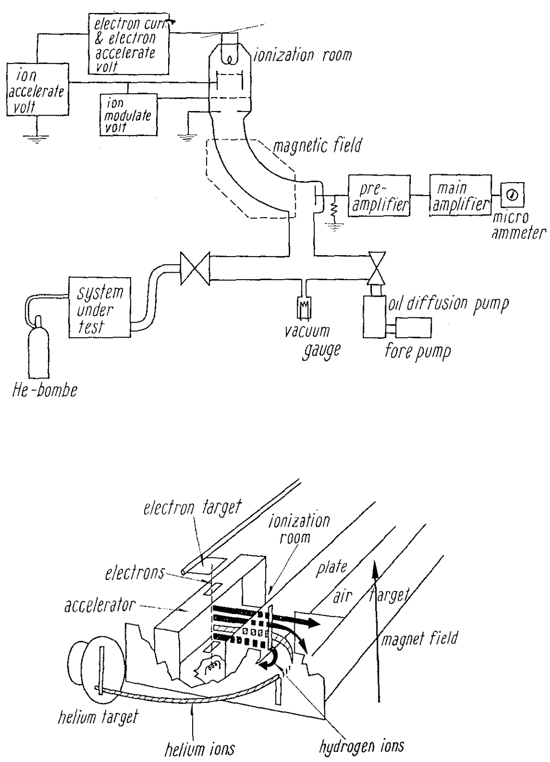
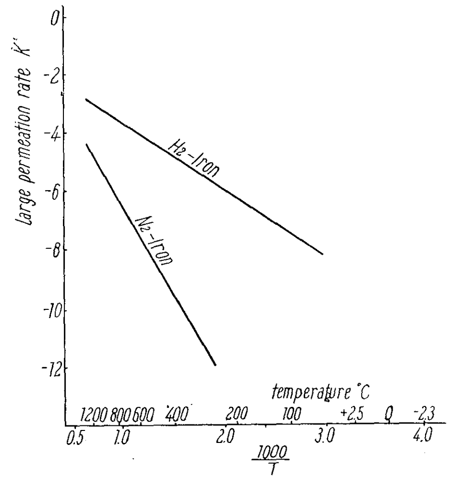


Fig. 11. Operation principle of helium leak-detector



$q=KAt(\sqrt{P_1}-\sqrt{P_2})/d$

- q: Total amount of material permeating a membrane (cm^3)
- K: Permeating velocity constant
- A: Area of membrane exposed (cm^5)
- t: Time (sec)
- P_1: Gas pressure or high side (a.t.m.)
- P_2: Gas pressure on low side (a.t.m.)
- d: Thickness of membrane (mm)

Fig. 12. Diffusion of gases in iron

Treatments of materials; All materials to be used as tank wall and in vacuum tank of pumpless rectifier should be sufficiently evacuated before assembling work, because insufficiently treated materials trends to liberate adsorbed gases into vacuum during operating conditions of rectifier. It is very difficult to degas the artificial graphite used as electrodes. We, in our Company, built a large vacuum furnace operated in very high temperature for pretreatment of graphite. Steel plates of vessel wall also liberate gases into vacuum as illustrated by some test results in Fig. 13 and should be sufficiently pretreated. After all, the reliability of pumpless rectifier depends upon perfect pretreatments of all materials and formation process.

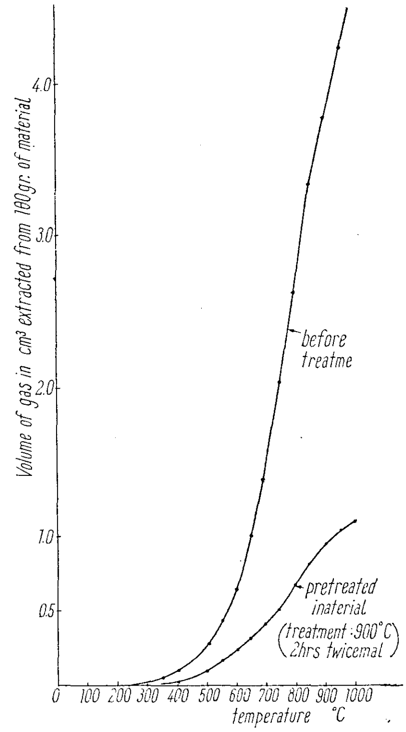
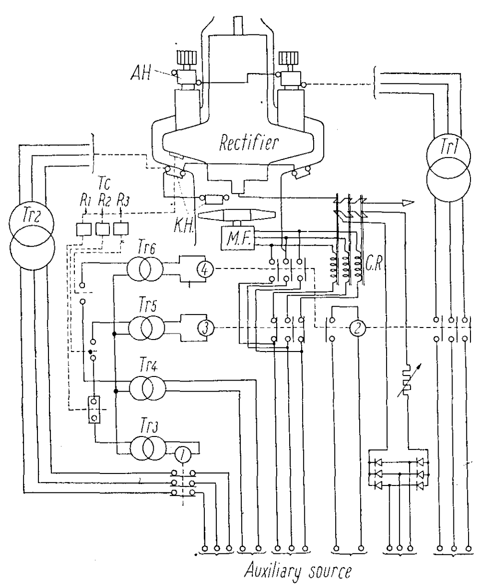


Fig. 13. Amount of extracted gas from steel plate

Temperature regulating system ; As characteristics of mercury arc rectifier depend upon mercury vapour behavior in vacuum vessel, it is very important to regulate the vessel temperature which controls the mercury vapour density. If temperature is too high, arc backs trend to occur and on the contrary when temperature is very low the danger for abnormal voltage exists. Temperature regulating system as shown in Fig. 14 is our automatic regulating method for our pumpless rectifier control. In the condition of high temperature, cooling fan is operated for cooling the vacuum vessel and in the conditions of low temperature, cathode heaters and anode heaters are suitably actuated. By these automatic control sufficient operation of rectifier is secured in the range of ambient temperature from 5°C to 40°C. These regulating apparata are arranged in a small cubicle together with ignition and excitation device and grid controlling apparatus and, as shown in Fig. 1, built on the common base frame with main vessel.



M.F. : Fan-motor
A.H. : Anode heater
K.H. : Cathode and vessel heater
Tr (1~6): Insulation transformer
1~4 : Magnet contactor
Tc R_1 : Thermal relay for K.H.
Tc R_2 : Thermal relay for Fan
Tc R_3 : Thermal relay for A.H.
CR : Saturable reactor

Fig. 14. Temperature controlling system for large vessels

IV. CHARACTERISTICS AS RECTIFIER

Important properties as rectifier are 1) value of arc-drop concerning the efficiency, 2) endurance against arc-back and 3) grid-control characteristics concerning the voltage or motor-speed controlling behaviors.

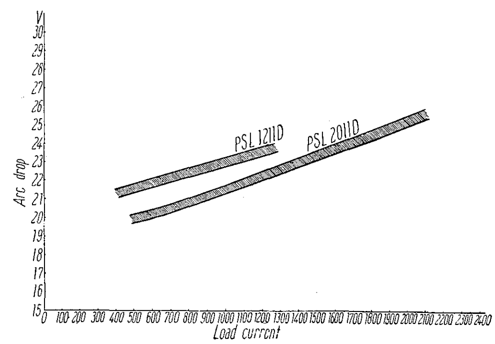
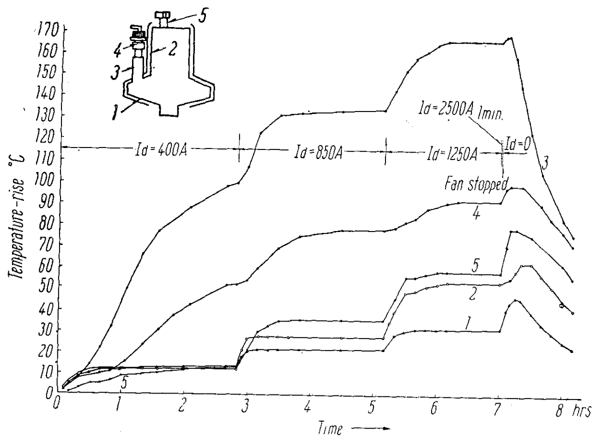


Fig. 15. Arc-drop curves for standard types

Characteristics of arc-drop of our standard vessels, PSL2011 and PSL1211, are shown in Fig. 15 and can be considered as 21~23 V in normal operating conditions. Our researches point that the attempts to reduce arc-drop values still more result in threatening the endurance of vessel against arc-backs.

Fig. 16 illustrates the temperature conditions of vacuum vessel in actual load test. The temperature of vessel bottom surface is considered as controlling temperature which rules the mercury vapour densities near anodes and consequently affects the endurance of rectifier vessel against arc-backs. From Fig. 16 can be seen that this controlling temperature does not exceed about 60°C in our standard vessel when the type current is loaded.

It is considered the deionization conditions of the space surrounding anode rules the arc-back charac-



1. Controlling temperature
2. Condensing room
3. Anode arm
4. Anode seal
5. Cathode seal

Id : Load current

Fig. 16. Transition of temperature during load test of PSL1211 vessel

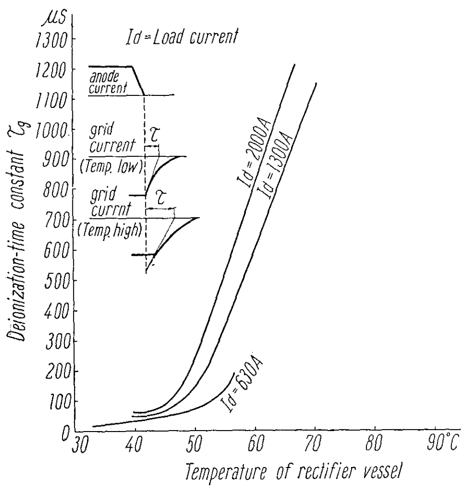


Fig. 17. Deionization-time-constant of the space surrounding the control-grid

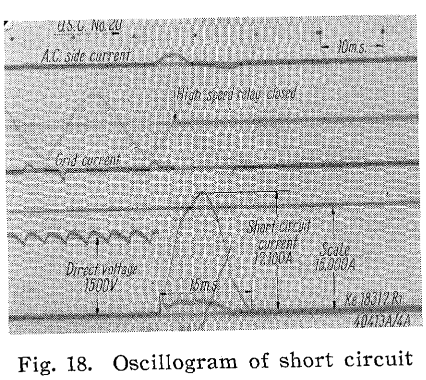
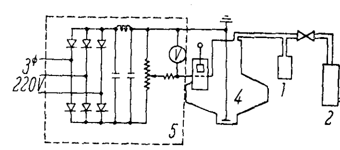


Fig. 18. Oscillogram of short circuit quenching test

teristics of rectifier vessel, and the deionization time constant of this space (τ_a) is usually used to figure the deionization conditions. Our standard rectifier vessels show $\tau_a = 60 \sim 90\ \mu s$ at vessel temperature $50° \sim 60°C$ and are proved having sufficient characteristics against arc-backs. Deionization time constant of the space in front of grid (τ_g) is similarly considered as important figure for characteristics of control grid. In Fig. 17, an example of our test results in τ_g about pumpless standard vessel is shown. τ_a is based on the dimensions of the space surrounding anode τ_g on the dimensions of grid and deionization baffle. Our long experiences prove these values of τ_g are sufficient for grid-control operations. In Fig. 18, an oscillogram of short circuit quenching test is shown.

V. SERVICE LIFE OF PUMPLESS VESSEL

I stated above in chapter III that causes of vacuum deterioration in pumpless rectifier tank is the leak through vessel wall and the liberation of adsorbed gases from employed materials. In concerning with the leakage, we use the helium detector of which is proved the accuracy of leak detection is $10^{-6}\ \mu$Hg-l/s in workshop appliance. As tank volume of our standard vessel PSL1211 is about 430 litres, vacuum deterioration rate of the manufactured with helium detector testing is under



1. Mac-leod vacuum gauge
2. Diffusion pump
3. Fore pump
4. Rectifier vessel under test
5. Measuring device

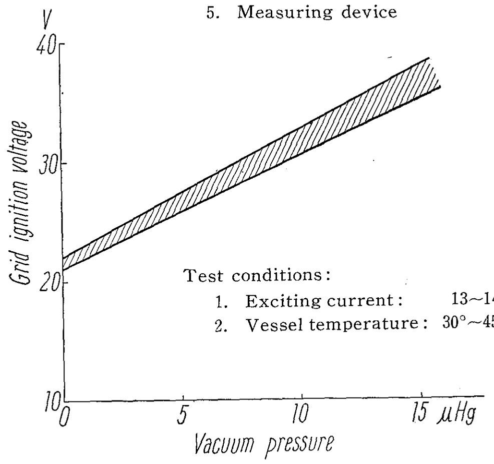


Fig. 19. An example curve of the relation between gride ignition voltage and vacuum pressure in vessel

$10^{-6}/430 = 2.32 \times 10^{-9}$ ℓ Hg/s. Therefore, if we consider the allowable limit of vacuum pressure in service operation as 5 Hg, the service life of the type PSL1211 is calculated as 70 years. Even when the vessel volume is a half of this type, the life of vessel vacuum is considered as 35 years. In concerning with the liberation of gases from employed materials, I related the sufficient treatments applied in manufacturing in our works. Results of our vacuum measurements about rectifiers in practical operations in these several years show no fears of vacuum deterioration.

Measuring method of vacuum pressure of pumpless rectifier vessels which no vacuum gauge is built on, can be divided in two groups ; One is the method in which spark voltage between electrodes is measured, and the other is the method in which ignition voltage of some electrode in existence of excited ions is measured, We, in our factory, employ the second method, because the first mothod needs

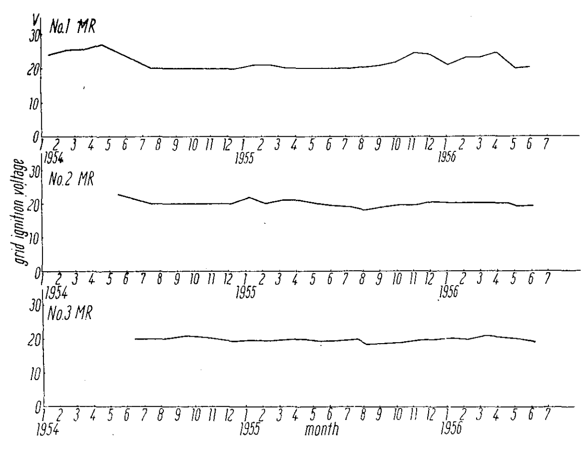


Fig. 20. An exapmle of vacuum inspection results in railway substation

very high d.c. voltage source and therefore does not suit for appliance in substations where rectifiers are in service. The measuring circuit is illustrated in Fig. 19 and the grid ignition voltage is measured by d.c. voltage in existence of rated exciting current at exciting anodes. Between grid ignition voltage and the vacuum pressure exists a relation as shown in Fig. 19 as an example, and we can estimate the vessel vacuum with sufficient accuracy of practical needs. Fig. 20 is a result obtained about pumpless rectifiers in a railway substation and shows no vacuum deterioration.

VI. VIEWS IN APPLICATIONS

Demerits of mercury arc rectifiers with pumps in the past were : 1) to have many troublesome accessories as pumping device and vacuum gauges and need for careful attention to hold good vacuum conditions, and 2) to be sensitive to the temperature and therefore need for much care to cooling or regulating vessel temperature. Pumpless rectifiers with automatic temperature controlling device are free from these defects and need little maintenance. In railway service, it became the modern tendency to project no-man substation or outdoor cubicle type substation. Fig. 22 is an example of arrangements in railway substation and Fig. 23 is a rectifier cubicle installed in an outdoor substation. As water-cooled rectifier needs recooling device and maintenance for water system and moreover the location of substation is limited by water supply, air-cooled rectifiers are particularly welcomed in railway service. Our Company can supply, as shown in Table 1, 6-anode air-cooled pumpless rectifier vessel of the output till 600 V–1,000 kW, 1,500 V–2,000 kW in heavy nominal rating.

Pumpless rectifiers have become to be accepted

Table 2. Supply list of pumpless rectifiers (standard types)

		Railway			Steel mill			Paper mill			General industry			Frequency changer			Electrolysis			Total
		A	B	C	A	B		A	B	D	B	D	E	B			A			
1953			3	4																7
1954			2										1	2						5
1955		4	13								1									18
1956		8	10		13			1	1	1				2						36
1957	Delivered	1	3																	4
	Under Manufacturing	20	3		12	5		1				3					1			75
Total		33	34	4	55	5		2	1	1	1	3	1	4			1			145

A : PSL2011 B : PSL1211 C : PSL1011 D : PSL0611 E : PSL0311

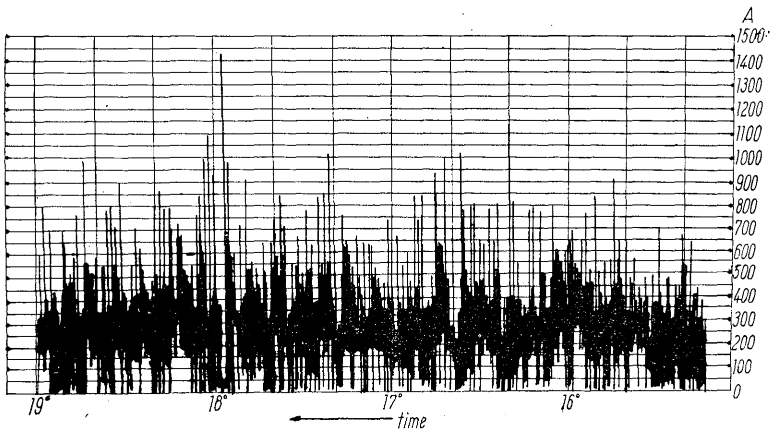


Fig. 21. Record of load variation of pumpless rectifier in Izumi railway substation

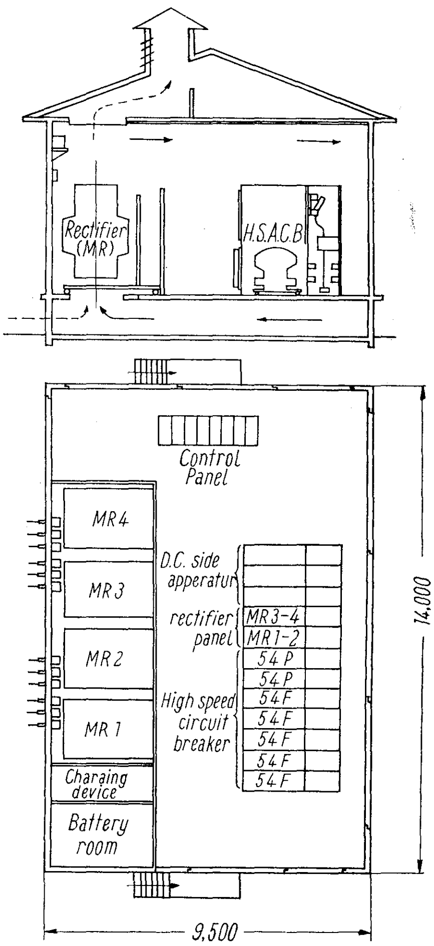


Fig. 22. Indoor arrangement of a railway pumpless rectifier substation (no-man and supervisory controlled)

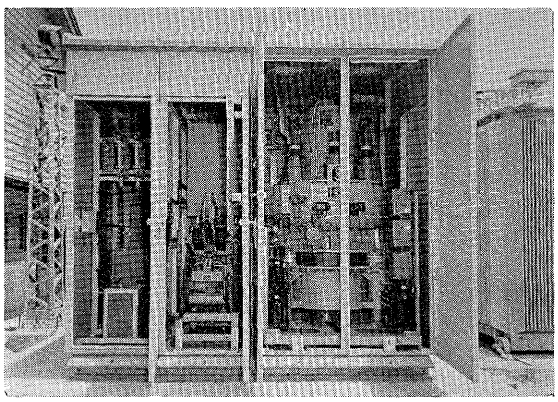


Fig. 23. Outdoor use cubicle type pumpless rectifier (Bamba substation Keihan Rialway Co.)

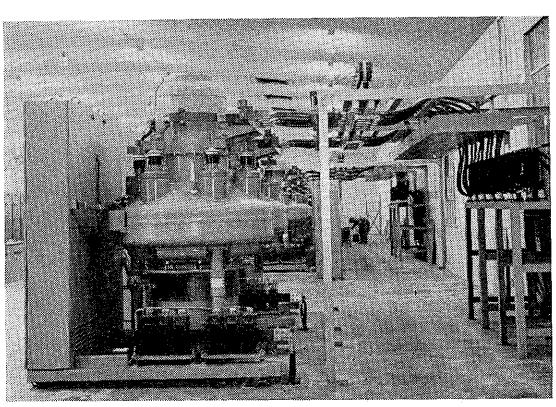


Fig. 24. Pumpless rectifier (type PSL2011) for a modern rod mill
(5×750 V, 2,000 A unit, Kobe Steel Mfg. Co.)

on a large scale in steel mill yards and other industries as d.c. voltage source and speed control devices of motors in various systems. In Fig. 24, a group of our standard type (PSL2011) rectifiers of large output for modern rod mill controlling source is shown. On account of the simplicity in maintenance and quick and accurate control characteristics, pumpless mercury arc rectifiers of small output are becoming to be applied for machine tools. The rectifier in Fig. 25 (type PSL0311) is the one used for reverse operation and braking of a vertical lathe of 12 meter diameter in our Kawasaki Works.

In Japan, static frequency changers which use mercury arc rectifier and inverter as its elements are now in service in considerable numbers. Pumpless rectifiers are also used in these regions with satisfactory results. In Fig. 26 are shown the changer set from 50 to 150 c/s used for pot-motors in Rayon works.

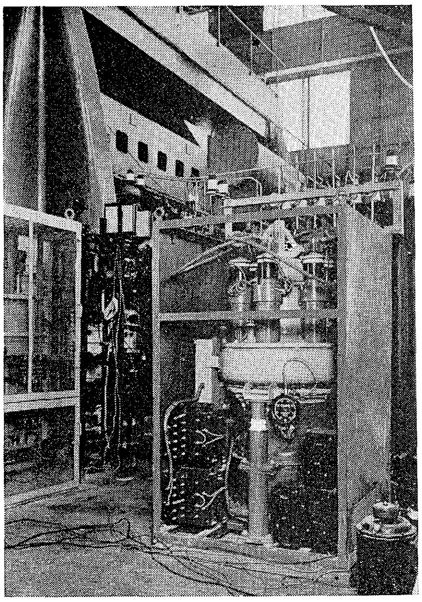


Fig. 25. Pumpless rectifier for a vertical lathe control
(Our own works)

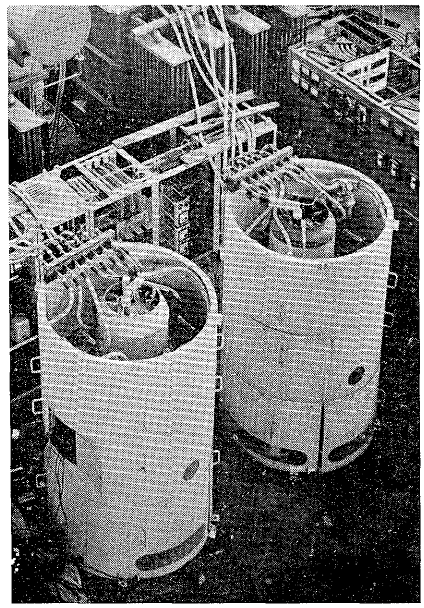


Fig. 26. Pumpless rectifiers used as 1,500 kW 50 cycles to 150 cycles static frequency changer for Rayon works
(Nobeoka works, Asahi Kasei Co.)