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〈기술해설〉

Progress of the Turbo Molecular Pump*

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1. Forward

The Turbo Molecular Pump (TMP) is rather new kind of vacuum pump. It has become a major pump of vacuum equipment with many recently improved features. This paper reports on the process of development and improvement, and views future trend of the TMP.

2. Development of the Turbo Molecular Pump

2.1. Origin of the TMP

The Molecular Drug Pump (Fig. 1), which was invented by Gaede (Germany) in 1912, initiated the molecular pumping principle. In 1958 Becker[1] (Germany) invented a structure similar to the present TMP, which is illustrated in Fig. 2. This pump has a hollow cylindrical casing with the shaft at the center of the cylinder. The shaft has multiple-stage turbine rotor blades and multiple-stage stator blades with similar shape to those of the rotor are located between the rotor blades. This pump achieves high pumping speed mechanically with the smaller size attaining ultra-high vacuum.

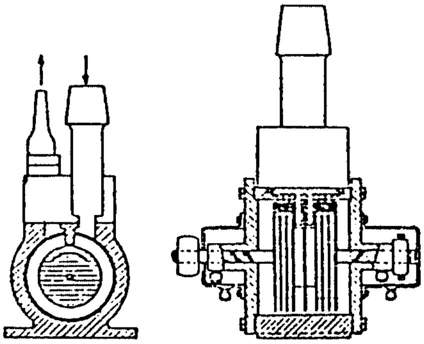

Fig. 1. Gaede's design of MDP (W. Gaede, 1913).

2.2. Rotor Support Bearing

The pumping principle of the TMP requires ultra-high-speed rotation. Generally, rotor rotates 20,000 to 90,000 rpm, giving 300 to 350 m/s peripheral speed at maximum diameter of the turbine blades. In the early generation, a liquid-oil-lubricated ball bearing was used as the rotor bearing, but it had a short life and suffered from vibration due to its high-speed rotation.

Recently, models with a grease-lubricated ball bearing which can operate at any attitude are available on the market. Also, models with ceramic ball bearings are available. ·

In 1976, Leybold Heraus A G (Germany) developed a totally magnetic levitated (5 controlled axes) TMP, as illustrate in Fig. 3. This pump was the

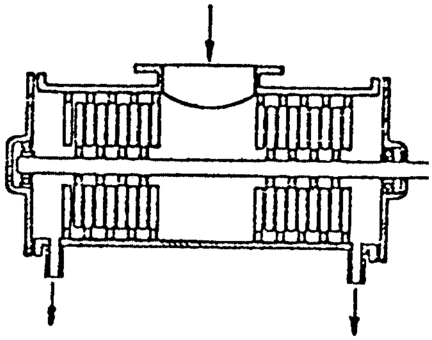

Fig. 2. Diagrammatic arrangement of TMP (W. Becker, 1958).

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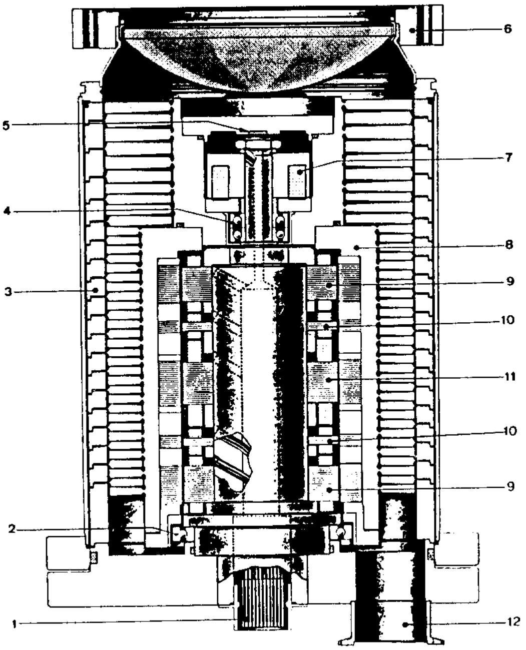


1 Current leadthrough
2 Dry safety bearing
3 Stator pack
4 Dry safety bearing
5 Axial sensor
6 High vacuum port
7 Axial magneto-bearing
8 Rotor
9 Radial magneto-bearing
10 Radial sensor
11 Medium frequency motor
12 Fore-vacuum port

Fig. 3. Sectional drawing of TMP (5 axes controlled : Turbovac 550 M).

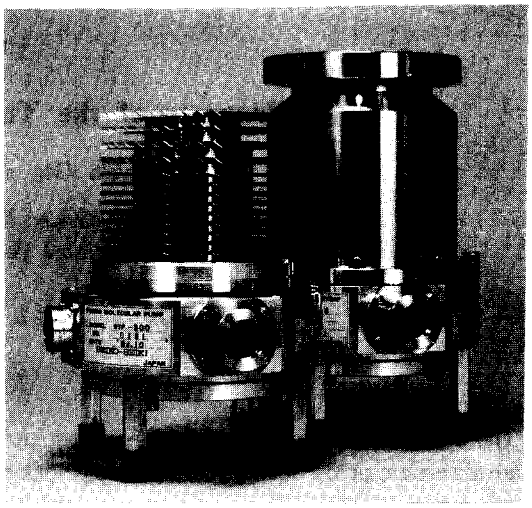


Fig. 4. Outside of TMP (STP-300).

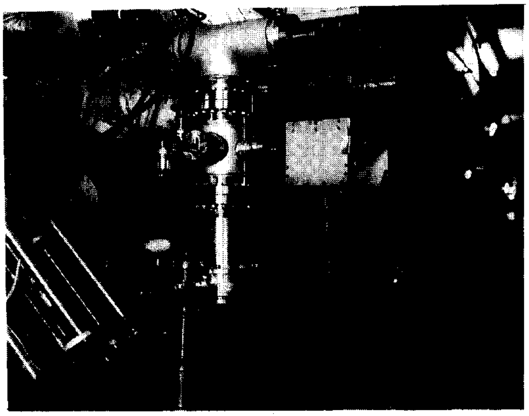


Fig. 5. Installed to KEK TRISTAN RF cavity (STP-300T).

first of really oil-free TMP with a contactless bearing, but it was too early for the industrial demand. Only a few hundred of these pumps were manufactured.

In 1983, Seiko Seiki (Japan) introduced a magnetic-bearing TMP with 3 controlled axes. This model is shown in Fig. 4. It combines the merits of the TMP and the magnetic bearing features of small size, low vibration, low acoustic noise and complete absence of oil.

These merits of TMP with a magnetic bearing are widely recognized in application to scanning electron microscope (SEM), analytical instruments and large experimental facilities for physics.

About one hundred of these pumps are installed in the synchrotron radiation ring of KEK TRISTAN (High Energy Physics Laboratory at Tsukuba, Japan). One of the pump is shown in Fig. 5. This pump (STP-300T) was specially developed for TRISTAN's all-aluminum-alloy vacuum system, including radiation-proof characteristics etc., based on ordinary model STP-300 with 300 l/s pumping speed.

With this successful introduction, about a half of TMP sales consist of the magnetic bearing model in the Japanese market. Many manufacturers have developed TMPs with magnetic bearing. These include one-axis control models (Fig. 6), five-axes control models with turbine and screw compound rotor (Fig. 7) and three-axes control models (Fig. 8).

The pump structure is explained with reference to Fig. 8 (three axes model). The main components

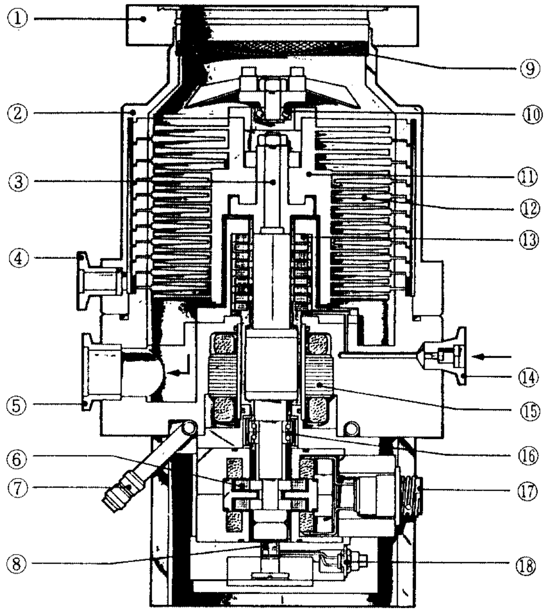


Fig. 6. Sectional drawing of TMP (1 axis controlled : Turbovac 340M).

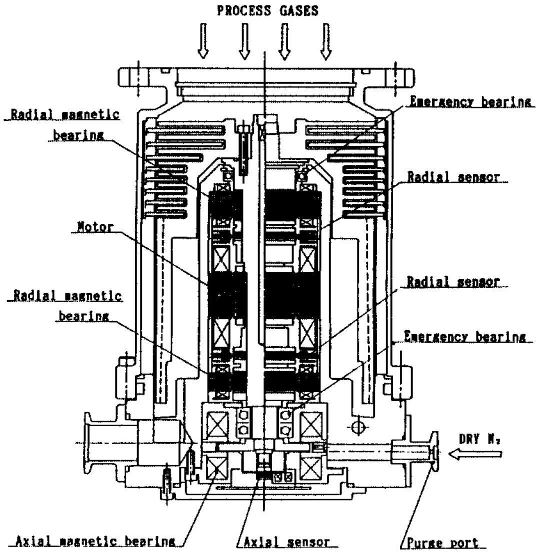
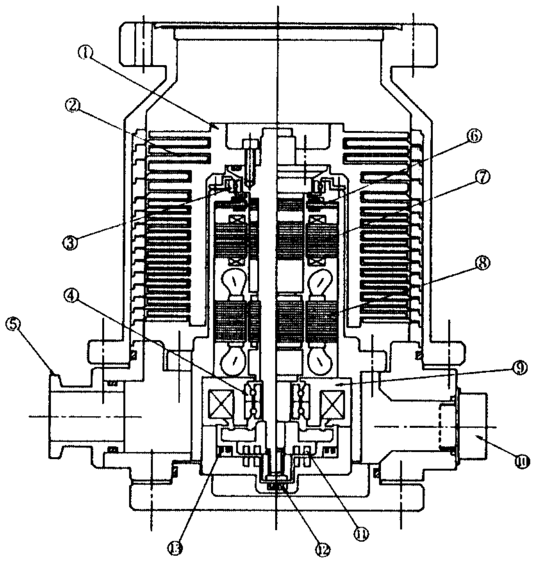


Fig. 7. Sectional drawing of TMP.
(5 axes controlled/tubine and screw compound rotor: STP-H600C)

are rotor blades①, stator blades②, high-frequency motor⑧, magnetic bearings⑥⑦ and housing. The blade stagger angle of the rotor① and the stator② is opposite each other and the stages of the rotor blades and stator blades are alternate.



① Rotor blade
② Stator blade
③④ Protective dry bearing
⑤ Exhaust port
⑥ Radial sensor
⑦ Radial electromagnet
⑧ High-frequency motor
⑨ Axial electromagnet
⑩ Connector
⑪ Permanent magnet
⑫ Axial sensor
⑬ Rotating sensor

Fig. 8. Sectional drawing of TMP.
(3 axes controlled : STP-300).

The fast-rotating blades assembly of the rotor is driven by a high-freqency motor. The rotation speed limit is defined by the permissible stress of the rotor blade material, which is usually a high-specific-aluminum alloy (duralumin).

The three axes magnetic bearings consist of an active radial bearing, and an active axial but passive radial bearing. The active radial bearing keeps the shaft location constant by control with two degrees of freedom in the radial bearing gap by the aid of radial displacement sensors⑥, two pairs of electromagnets and their control circuit.

The active axial but passive radial bearing keeps the shaft axial location constant by control with one degree of freedom in the axial direction. This unique axial bearing works with an axial displacement sensor⑬, a ring electromagnet with annular groove⑨, two pairs of permanent magnet rings⑪ and one control circuit. This structure generates passive centering force by the aid of the ring magnet.

By this arrangement, all the rotating members are not only supported absolutely without any contact but also operated without any lubricant (absolutely dry condition)[2].

Protective dry ball bearings with solid lubricant film are provided for accidental electricity supply failure, but the rotor shaft does not touch this protective dry bearing in normal operation.

In 1987, Mitsubishi Heavy Industry (Japan) developed a TMP with permanent magnet radial bearing and a hydro-dynamic oil bearing with spiral grooves on the spherical surface. This bearing is similar in structure to that of the centrifugal separator.

As described above, the feature of the TMP depend on the features of the bearing. A feature comparison of the TMPs with the different types of bearing is given in the Table 1.

2.3. Rotor Configuration

The structure of the turbine is similar to that of an electric generator drive turbine composed of 10 to 20 sets of rotating and stationary blades.

The pumping principle of the TMP was explained precisely by Kruger, Shapiro[3] and Sawada[4]. In this paper, an outline of the principle is given.

The form of the turbine blade of the TMP is very simple compared with that of the generator turbine, because the aerodynamic effect between the blade and the gas is negligible in the low-pressure (lower than 0.1 Pa or 1×10^{-3} Torr) molecular flow range. In other words, the possibility of collision of gas molecules with each other is very low because the mean free path of the gas molecules is very long in the molecular flow range.

The row of the turbine blades shown in Fig. 9

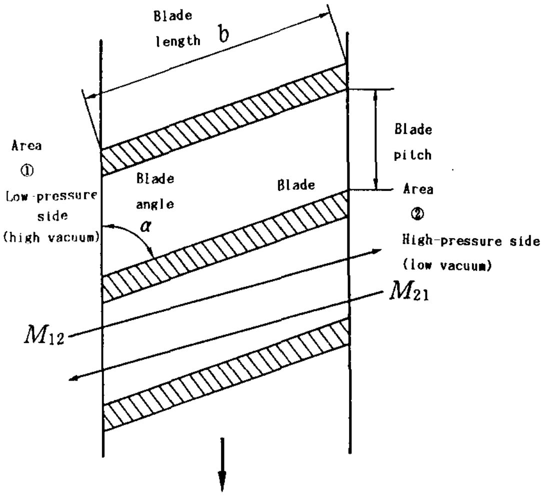


Fig. 9. Shape of turbo molecular pump singles-stage cascade of blades.

Table 1. Comparison of each bearing type applied to TMP

Item \ Type	Ball bearing	Spiral groove bearing	Magnetic suspension bearing
Life of bearing	△ 2 to 3 year	○ Semipermanent	◎ Permanent
Maintenance	× Need to exchange oil	◎ Free	◎ Free
Lubricant	× Much	○ Little	◎ Nor required
High rotation speed	△	○	○
Vibration and noise	○	◎	◎
Mounting angle	△ 0~20°	△ 0~10°	◎ Free
Dimension and weight	○	○	○
Carrying	△ Need to extract oil	△ Need to extract oil	○
Price	○	○	△

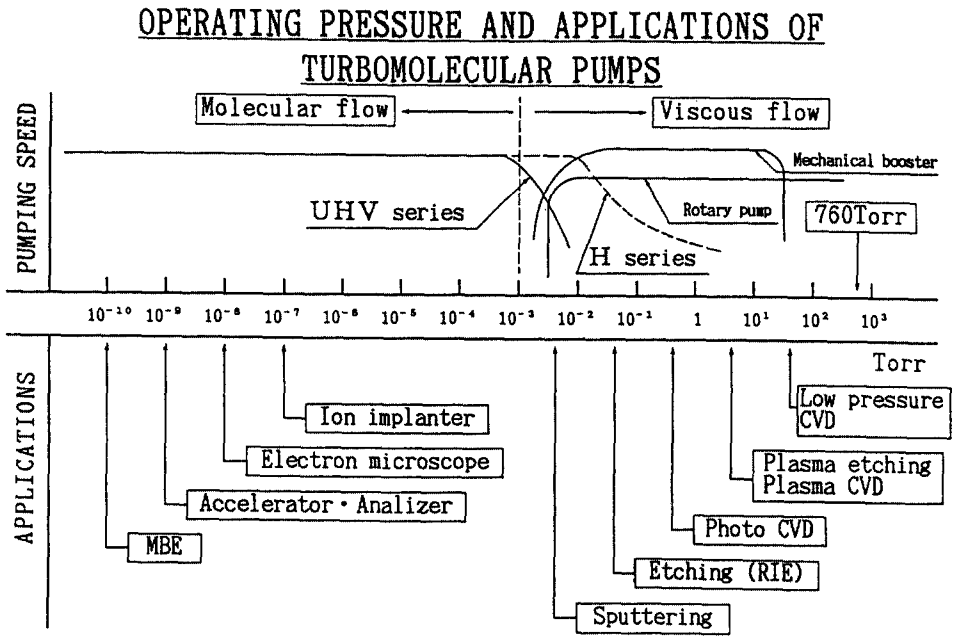


Fig. 10. Operating pressure and applications of TMP.

moves towards the direction of the arrow. Fast motion of the row of blades creates pressure difference between the two sides of the row. This figure represents a single stage of the turbine. Maximum compression ratio K_{max} and maximum pumping speed W_{max} of the single-stage turbine are represented in the following formula.

$$K_{max}=M_{ij}/M_{ji}, \qquad W_{max}=M_{ij}-M_{ji}$$

Where M_{ij} : Probability of molecule passage from region i to region j

α : stagger angle of the blade

b : blade width

s : blade pitch (spacing)

Probability M_{ij} is determined by the blade form parameters (α, b, s and height) and the speed of the blade and the gas molecules. To calculate the performance of the total pump unit, the probability of each stage must be multiplied together. Generally the probability is obtained by Monte Carlo method.

With this turbine form, the pumping effect is limited only by the pressure of the molecular flow range. The operating pressure range and aplications of the TMP are shown in Fig. 10. In the early generation, the scope of application of the TMP was limited to SEM, analytical instruments, accelerators, etc. (UHV Ultra High Vacuum series line in Fig. 10).

In 1986, Osaka Vacuum Ltd. (Japan) developed a turbine and screw compound molecular pump which can be operated in a higher pressure range. (H series represented by dotted line in Fig. 11) With this rotor structure (Fig. 7), TMPs came to be operated up to the medium flow range (up to several Torr or hundreds of Pa). This medium flow range TMP expanded the TMP market share in all kinds of high vacuum pump by use in a large range of semiconductor manufacturing equipment including dry etchers, sputter equipment, etc.

3. Application of Turbo Molecular Pump

3.1. Application to Semiconductor Manufacturing

Recently, the TMP has become a more important component of semiconductor manufacturing equipment. Corrosion proofing of the vacuum pump is important. For this purpose, anti-corrosive surface treatment is applied to the internal surface of the

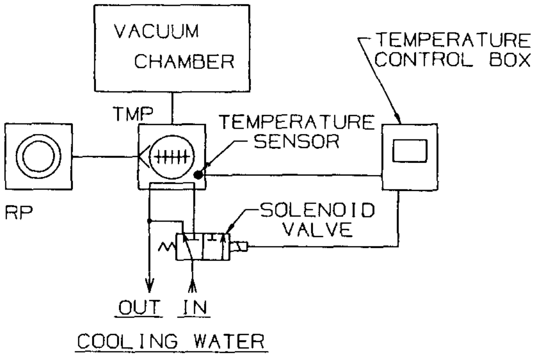


Fig. 11. Countermeasure of the deposit in the vacuum pump.

TMPs in chemical use. Especially for active gas pumping applications, magnetic bearings are superior to oil bearings because they are lubricant trouble free.

A problem to the TMP in chemical process is deposition. For example, serious problems result from heavy deposits on pump components. These deposits are the chemical reaction product of aluminum dry etching. When the TMP pumps out reacting gas such as S_iCl_4, Cl_2, BCl_3, etc., $AlCl_3$ deposits stick to the inside of the outlet of the TMP because relatively high pressure with water rich in molecules at outlet side makes the gas form deposits. This chemical reaction deposit fills the internal clearance between the rotor and stator (about 1 mm), and stops pump rotation.

Constant temperature control of the TMP, as shown in Fig. 11 is used as the countermeasure for the deposition problem. The control target temperature is decided by the gas nature and the kind of deposit. However, deposition can generally be suppressed by keeping the gas passage temperature above 60℃.

Temperature variation versus inlet gas pressure with temperature controlled and decontrolled is shown in Fig. 12. The heat sources of the TMP are the driving motor and the magnetic bearings. The ordinary temperature of the TMP is 40℃ at molecular flow pressure, but the temperature is raised by higher inlet pressure than the molecular flow range. This controller keeps the TMP temperature constant by using cooling water and an electric heater whenever the inlet gas pressure varies. As an example of the effect of this controller in the aluminum etching process, the maintenance period is extended from one month to over two years.

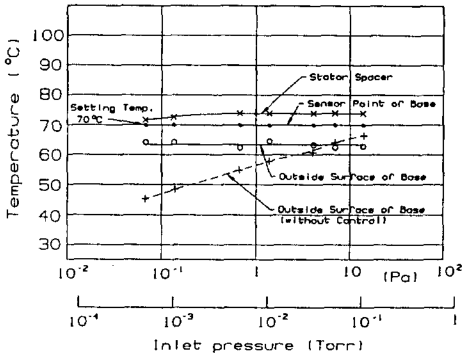


Fig. 12. Temperature of TMP with thermal control.

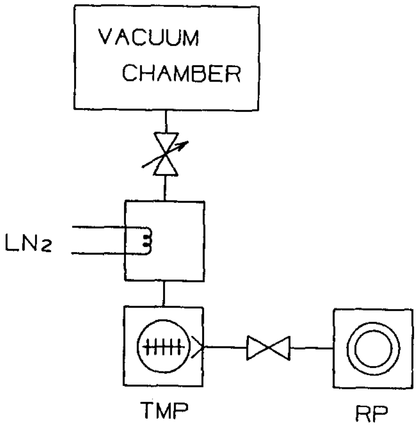


Fig. 13. Selective gas pumping system.

A cryogenic trap has been provided since 1990 for pump-up time shortening or for lowering the ultimate pressure. This trap, which includes a cryogenic pump, is attached to the inlet opening of the TMP, and improves the pumping efficiency for water molecules. This TMP with a cryogenic trap is used mainly in the sputtering process in semiconductor manufacturing.

A vacuum puming system with a liquid nitrogen cryogenic trap is illustrated on Fig. 13. This cryogenic panel traps water molecules effectively. The throttle valve controls the pumping speed of other process gasses for manufacturing process require-

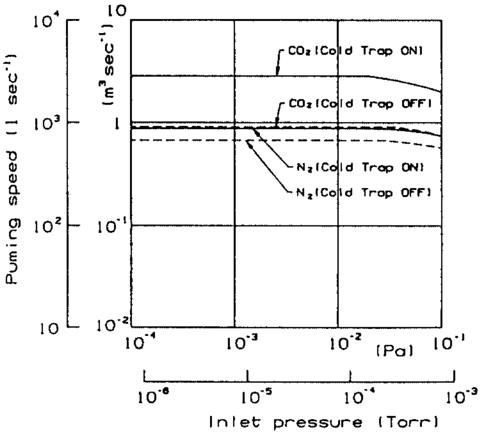


Fig. 14. Pumping speed with cryo-panel.

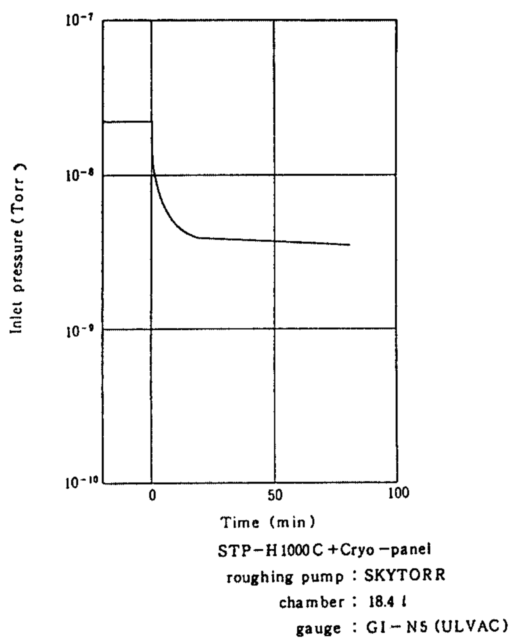


Fig. 15. Pumpdown curve with cryo-panel.

ments.

The effect of the cryogenic trap is shown of Fig. 14. The pumping speed of N_2 gas was increased by 30%, and that of CO_2 was increased 3.2 times with the cryogenic trap. CO_2 gas was pumped instead of water molecules. The pressure behavior up to the ultimate pressure with the cryogenic trap is shown in Fig. 15.

The TMP with cryogenic trap has started to replace cryogenic vacuum pump for sputtering equipment. In actual application, the cold trap temperature is varied by use of a refrigeration system instead of liquid nitrogen, to optimize trap temperature for the gas which is to be trapped.

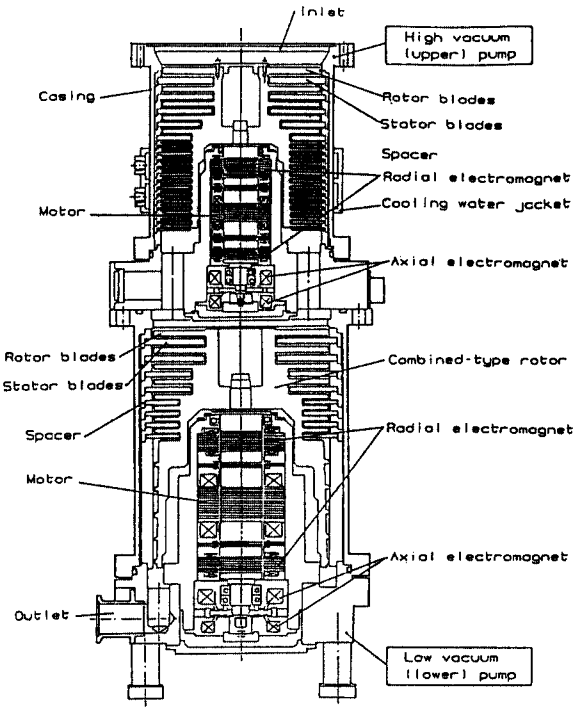


Fig. 16. Sectional drawing of the tandem TMP.

3.2. For Extremely High Vacuum (EHV)

It is believed that the ultimate pressure of the TMP is limited to 10^{-8} Pa (10^{-10} Torr). To break this barrier, and to make an ultra-high-vacuum (UHV) pump suitable for semiconductor manufacturing, development work was done to reach a 10^{-10} Pa (10^{-12} Torr) ultimate pressure by TMP without any gas absorption pump.

A cross-sectional view of the consequentry developed tandem TMP is illustrated in Fig. 16. To reach extremely high vacuum (EHV), the design improvement in compression ratio for H_2 was 5×10^8, and 0.3 μm to 0.6 μm R_{max} mirror surface finish was applied to the components for minimize gas emission from the internal surface of the pump.

The pressure behavior on reaching the ultimate

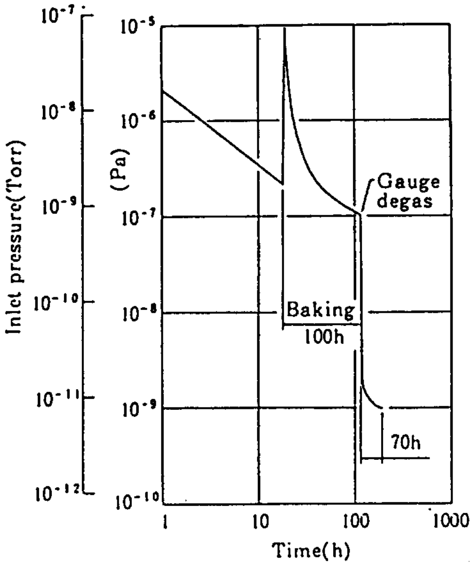


Fig. 17. Pumpdowm curve (Tandem TMP).
The ultimate pressure with water cooling is 1×10^{-9} Pa.

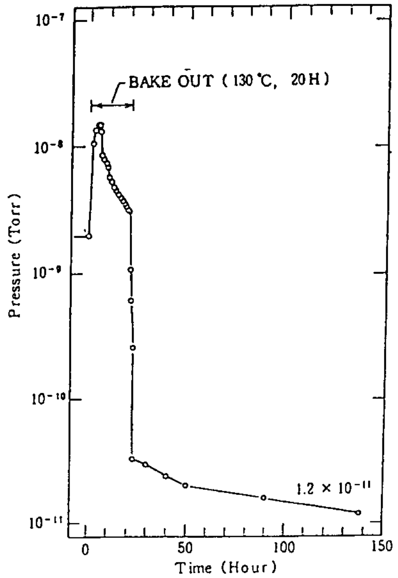


Fig. 18. The ultimate pressure measured by OHMI laboratory of Tohoku university. (Tandem TMP)

value (8×10^{-12} Torr) of the pump is illustrated in Fig. 17. The pressure behavior of the sputtering chamber with this tandem TMP is also illustrated on Fig. 18. The internal surface of this stainless steel sputtering chamber is chemically stabilized [5].

One model recorded 1.3×10^{-10} Pa (1×10^{-12} Torr) by minimizing gas emission more effectively.

4. Probable Future Trend

TMPs with magnetic bearings will be in the main stream of high vacuum pumps, with these improvement. Pump with disign which eliminates the back up battery for the electricity supply failure, shrinks the electonics size by half and adds various control functions using microprocessors, will be finished and introduced to the market in 1993.

Even higher pumping performance in a wider pressure range will be required for TMPs and primary pumps in total vacuum pump systems when they are attached to semiconductor manufacturing equipment.

Pumping speed and compression ratio are poor in the range from a few Torr to 10^{-2} Torr with present TMPs and dry pump systems.

In the future, single-unit vacuum pump effective from ambient pressure to ultra-high-vacuum based on new concepts should be developed.

The turbo molecular pump will maintain and enhance its important position as a high-vacuum-pump with further operational and functional improvements.

References

1. W. Becker, Vacuum-Technic, **7**, 149 (1958).
2. H. Ishimaru, K. Narushima, "Background Pressure Dependency of Turbo Molecular Pump with Magnetic Bearing" KEK Report 1984-11 (in Japanese).
3. C. H. Kruger, A. H. Shapiro, "The Axial Flow Compressor in the Free Molecular Range" (Rarefield Dynamics Gas Supplement), Academic Press, New York, N.Y., 117 (1961).
4. M. Sawada, *et al.* "Research on the Axial Flow Molecular Pump" 2nd report, Paper Japan Society of Mechanical Engineers, Vol. 36, No. 285 781 (1970) (in Japanese).
5. C. Urano, *et al.* "Tandem Turbo Molecular Pump with Magnetic Bearing" Ultra Clean Technology, Vol. No. 1 **51**, 233 (1990) (in Japanese).