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FUJI ELECTROMAGNETIC PUMPS FOR LIQUID SODIUM

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I. INTRODUCTION

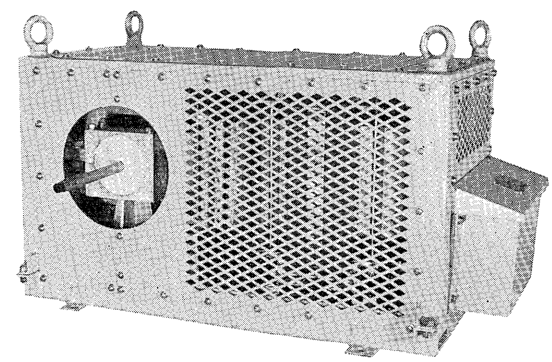
The fast breeder reactor which is now being developed on a national project in Japan and is said to be the power plant of the future employs liquid sodium as coolant. Liquid sodium has excellent characteristics as a coolant for atomic reactors, but it is very active chemically and reacts especially violently with water. Therefore, equipment with which the sodium comes in contact must have special properties.

At Fuji Electric, research into the development of a sodium cooled fast breeder reactor has led to the completion of series of the Faraday type electromagnetic liquid sodium pumps which insure efficient transport of liquid sodium. This series was delivered to Kawasaki Heavy Industries. A total of 5 of these pumps as follows were installed in Power Reactor and Neuclear Fuel Development Corpolation Oarai Works.

(1) A main loop circulation pump especially developed for sodium with a capacity of 200 *l*/min. 2 kg/cm^2
(2) A main loop purification pump with a capacity of 40 *l*/min. 1.5 kg/cm^2
(3) A testing loop mother loop pump with a capacity of 50 *l*/min. 2 kg/cm^2
(4) A mother loop of mass transport loop pump with a capacity of 10 *l*/min. 3 kg/cm^2
(5) A hot steel loop pump with a capacity of 6 *l*/min. 2.5 kg/cm^2

These electromagnetic pumps feature special electrode parts. The electrode part which is the most important component of the pump is specially processed so that the electrodes and the sodium duct form a single unit. This completely eliminates defects due to electrical fusion of the electrodes which was such a problem in pumps made by other makers This feature means that the long term reliability of the pumps is extremely high (patent applied for).

In addition to the products described above for Kawasaki Heavy Industries Ltd. and Power Reactor and Neuclear Fuel Development Corporation, Fuji Electric has also received inquiries from Japan Atomic Energy Research Institute, universities and manufacturing companies. This article will give general outline of Fuji electromagnetic pumps for liquid sodium.


(a) External view

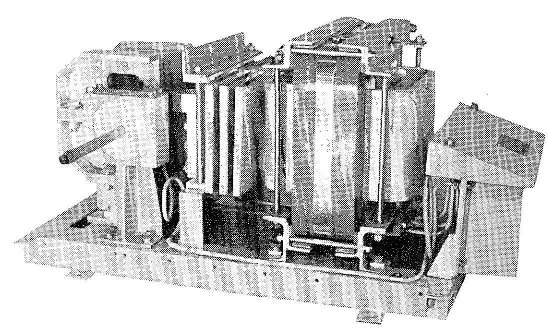

(b) View with protective casing removed

Fig. 1 Fuji electromagnetic pump for liquid sodium (50 *l*/min)

II. PRINCIPLES OF THE PUMPS

1. Operating Principles

The princle of series of the Faraday type electromagnetic pumps is shown in *Fig. 2*. The electrodes are placed in a sodium duct made from materials such as stainless steels (SUS27, SUS32) which have characteristics of high electrical resistivity facter, non-magnetic and high corrosion proof in respect to liquid sodium of high temperatures (500～600°C). A current flows through the electrodes into the liquid sodium. An iron core is placed perpendicular to the direction of current flow and this causes magnetic field to be created at right angles to the electric

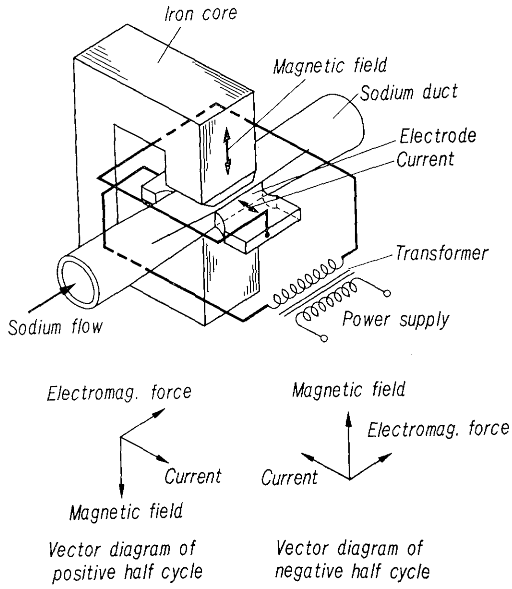


Fig. 2 Principle diagram

current. Due to this current and magnetic field in the liquid sodium, the so-called Faraday law causes an electromagnetic force to occur in the direction shown by the arrow in the diagram.

The current flowing in the sodium can be either a-c or d-c. In this series of electromagnetic pumps, a current with a magnitude between several thousand and ten thousand amperes is required. If d-c current were employed, it would require a large d-c power supply which would usually be uneconomical except for pumps with small capacities. Therefore, the majority of systems at present employ the a-c system since it is easy to obtain large currents with low voltage/high current transformers.

When the a-c system is used, the current polarity is reversed every half cycle which means that it is also necessary to reverse the magnetic field polarity in accordance with the current polarity in order to obtain a constant electromagnetic force. Therefore, these pumps employ a series winding in which the electrode current is directly on the iron core as shown in *Fig. 2*. In this way, the magnetic field changes in phase with current changes so that it is possible to obtain electromagnetic force in a constant direction and this means a constant direction of pump pressure.

2. Relation Between Pump Characteristics and Current, Field and Duct Dimensions

The basic dimensions of the duct part are as shown in *Fig. 3*. When the current flowing from the electrode into the sodium is I (effective value), and the magnetic field perpendicular to the current is B (maximum value), the electromagnetic force F created in the sodium can be represented by the following equation.

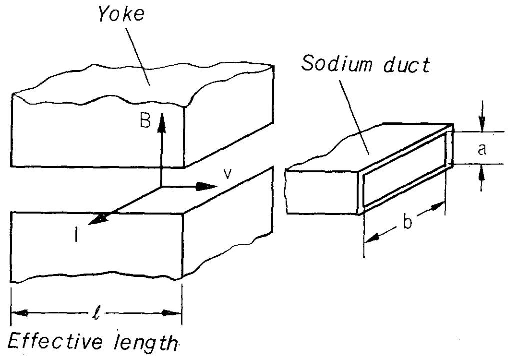


Fig. 3 Basic dimensions of duct part

$$F=\frac{1}{\sqrt{2}}I\cdot B\cdot b \quad \cdots\cdots (1)$$

where $\sqrt{2}$: coefficient for the sine wave of the current and magnetic field

b : the width of the duct and corresponding to the length of the current path in the sodium

Since the above electromagnetic force F arises in a crossection of the duct, the pump pressure P can be represented as follows:

$$P=\frac{F}{a\cdot b}=\frac{1}{\sqrt{2}}\frac{I\cdot B}{a} \quad \cdots\cdots (2)$$

where a : height of duct

$a\cdot b$: sectional area of the duct

If the velocity of the sodium within the duct is v, the flow rate Q of the pump can be expressed as follows:

$$Q=a\cdot b\cdot v \quad \cdots\cdots (3)$$

Since the pump output is the products of the pressure and flow rate,

$$\begin{aligned} P\cdot Q &= \left(\frac{1}{\sqrt{2}}\frac{I\cdot B}{a}\right)(a\cdot b\cdot v) \\ &= I\cdot\left(\frac{1}{\sqrt{2}}\cdot B\cdot b\cdot v\right) \\ &= I\cdot V \quad \cdots\cdots (4) \end{aligned}$$

$(1/\sqrt{2})\cdot B\cdot b\cdot v$ is corresponding to the voltage V (effective value) induced in the sodium, and IV represents the electrical input. Thus it is possible to understand the relation between the electrical input and the mechanical output (this is a theoretical value in which the electrical resistivity loss, etc. is neglected).

The effective length l of the duct (portion of the duct length in which the magnetic field crosses the current) can not be substituted directly in the above equation but it can be determined as follows from the relation of the current density of the electrodes. The electrode current density must be kept at or below the permissible value i_0 because of temperature rises and, therefore, the effective length l of the duct can be expressed as follows.

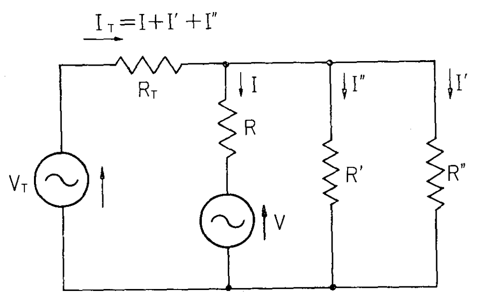
$$l=\frac{I}{a \cdot i_0} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

3. Pump Pressure/Flow Characteristics

According to equation (2), the pump pressure P is proportional to the electric current flowing in the sodium. The current flowing in the sodium consists of the current I which crosses the magnetic field and is employed in pump operation, the current I' which is reactive and flows in the region of the pump operating part where there is no cross field, and the current I'' which flows via the stainless steel duct. It is advisable to keep the values of I' and I'' as low as possible. Considering the voltage $V=\left(\frac{1}{\sqrt{2}} \cdot B \cdot b \cdot v\right)$ which is induced in the sodium and resistance of the stainless steel duct and copper lead, the eqaivalent pump circuit is as shown in *Fig. 4*.

If the voltage supplied to the pump is constant, the effective current I flowing in the sodium is reduced when the pump flow Q, i.e. the sodium speed v, is increased. As is evident from the equivalent circuit, the voltage $V=\left(\frac{1}{\sqrt{2}} \cdot B \cdot b \cdot v\right)$ induced in the sodium increases when the velocity v is raised. Therefore, the relation $\frac{I}{I'+I''}$ between the effective current I flowing from the electrodes into the sodium which contributes to pump operation and the reactive currents I' and I'' which have nothing to do with pump operation, is changed. The main reason for this is the reduction in the effective current I by the pressure.

Therefore, the curve of pressure reduction in respect to flow is as shown by the solid line in *Fig. 5*. As the flow increases, the increase in fluid pressure loss in the pump duct and piping is almost the square of the flow. Thus the pressure tends to increase much more rapidly when the flow is large as can be seen from the dotted line in *Fig. 5*.



R: Sodium resistance of pump operation part
R': Sodium resistance of area surrounding pump
R'': Resistance of stainless steel duct
I_T: Total pump input current
V_T: Pump input voltage

Fig. 4 Equivalent circuit of electromagnetic pumps

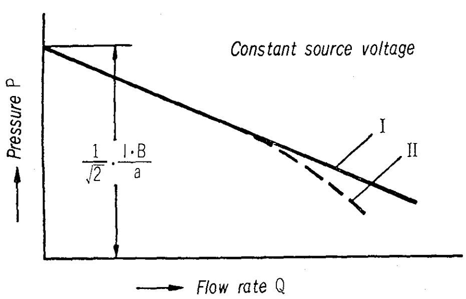


Fig. 5 Typical characteristics of pressure and flow

III. PROPERTIES OF SODIUM AND HIGH TEMPERATURE CHARACTERISTICS OF STAINLESS STEEL

Before the construction and series of the Fuji electromagnetic pumps are introduced, a simple explanation of the properties of sodium and high temperature characteristics of stainless steel will be given to aid in handling the high temperature sodium.

1. Properties of Sodium

Table 1 gives the properties of sodium and *Fig. 6* is the electrical resistivity of the sodium in respect to temperature. As is evident from *Table 1,* (1) the liquid sodium temperature range 98~883°C (normal pressure) is highly suitable for use as a coolant in atomic reactors; (2) the thermal conductivity is extremely high (about 100 times that of water under normal temperatures) and the specific heat of 0.3 cal/g·deg is also rather high (water is 1 cal/g·deg); (3)

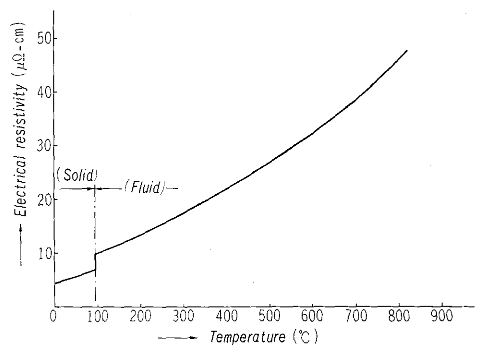


Fig. 6 Electrical resistivity of sodium

***Table 1* Properties of Sodium**

Atomic number		11
Atomic weight		22.99
Melting temperature (°C)		97.8
Boiling temperature (°C)		882.9
Specific weight	at 20°C	0.97
	at 500°C	0.83
Specific heat (cal/g·deg°C) at 500°C		0.30
Viscosity coefficient (centipoise) at 500°C		0.24
Thermal conductivity (cal/cm·sec·deg°C) at 500°C		0.16

the specific gravity of 0.83 is less than that of water; and (4) the viscosity coefficient is also low, only 0.24 centipoise as compared with 1.0 centipoise for water. The electrical resistivity varies in accordance with the temperature but its 9.7~46 $\mu\Omega\cdot$cm range (liquid) make it good conductor after copper and aluminum.

Chemically, sodium is a monad which reacts strongly with the halogens and oxygen, and combines with hydrogen. It reacts violently with water to form hydrogen and caustic soda.

When liquid sodium is used, selection of the materials for parts of the duct and piping which come into direct contact with the sodium is extremely important, but sodium has many advantages from the construction standpoint. Naturally it can not be used carelessly, but the atomic radius of sodium is large when compared with other metallic elements used for construction and the electronegative level is low. Therefore it can be used with elements such as iron, chromium, nickel, cobalt and molybdenum which have a low solubility in sodium. Since stainless steel can also be used at the 600° temperatures required in atomic reactors, there are many advantages in respect to existing techniques.

2. High Temperature Characteristics of Stainless Steel

The main reason why stainless steel in employed with sodium is given in section 1. However, the following factors concerning its suitability must be considered. These, factors include high temperature creep, high temperature fatigue, thermal shock and high temperature corrosion.

There are many types of stainless steel depending on the purpose of application. Classifying according to structure, there are martensite steel, ferrite steel, and austenite steel. Austenite steel is best in terms of non-magnetism, thermal resistivity, corrosion-proofing and weldability. Typical types of austenite steel are SUS 27 and SUS 32 and it was these types which were used in the pump duct part. *Table 2* gives the chemical composition of these two types of stainless steel, and *Fig. 7* shows a typical temperature vs. strength curve for SUS 27. In addition to mechanical stress, this figure also shows the rupture in respect to time, the stress in respect to a 1% creep and the maximum permissible stress according to the ASME Boiler Code.

It is necessary to consider these stresses in the

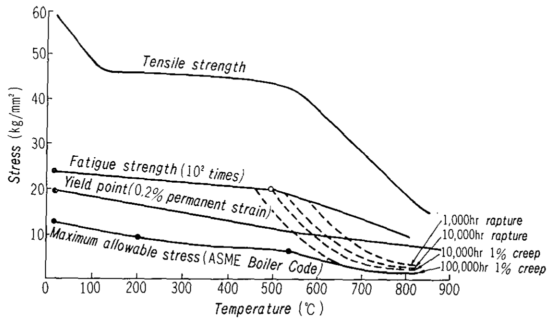


Fig. 7 **Relation between mechanical strength and temperature for stainless steel**

design stage and allow for sufficient safety factors. Thermal shock is avoided by preventing the liberation of internal stress when there is a sharp temperature gradient. Since corrosion is a problem concerned with the structure of the metal, it is necessary to use methods in which the structure is not altered during processing.

IV. CONSTRUCTION AND SERIES OF FUJI ELECTROMAGNETIC PUMPS

1. Construction

An external view of the Fuji electromagnetic pump is shown in *Fig. 1 (a)*, while *Fig. 1 (b)* shows the same model with the protective frame removed. Once the pump has been installed in the loop, the protective frame can still be removed without effecting terminal connections or pump functions. Terminal are located on the top and side of the case, which insures greater safety.

As can be seen from *Fig. 1 (b)*, this pump contains a duct in which the pump pressure arises and an iron core. Beside these is a transformer which supplies low voltage/high current. Between them is a cooling fin to stop the heat from the high temperature duct. The construction has been rationalized for greater compactness.

The main features of this pump are as follows.

(1) Since the electrode section, the most important part of the pump, is specially constructed so that the electrode and the liquid sodium duct form a single unit, electrical fusion of the electrode which presented problems in pumps of other makers has been completely eliminated. *Fig. 8* shows an ex-

Table 2 **Chemical Composition of Stainless Steel**

Composition	Type of Steel		Chemical Composition							
	JIS	AISI	C	Si	Mn	P	S	Ni	Cr	Mo
18 Cr-8 Ni	SUS27	304	0.08 or less	1.00 or less	2.00 or less	0.040 or less	0.030 or less	8.00~ 11.00	18.00~ 20.00	
18 Cr-12 Ni-Mo	SUS32	316	0.08 or less	1.00 or less	2.00 or less	0.040 or less	0.030 or less	10.00~ 14.00	16.00~ 18.00	2.00~ 3.00

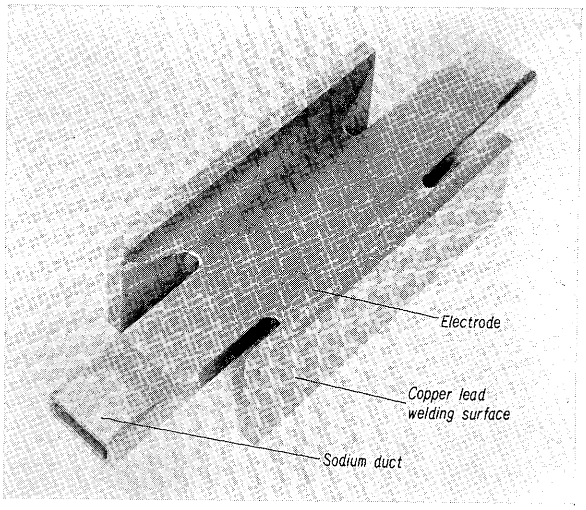


Fig. 8 Outer view of electrode part

ternal view of this type of electrode part. The duct and electrode are made from a single block of stainless steel. Sufficient distance has been provided between this part and the surface where the copper leads are welded so that electrode stress due to high temperature and current accumulation can be avoided. Since all welding is performed by means of an electronic beam, safety is assured. Therefore extremely high reliability can be maintained over long periods of operation.

(2) *F* or *H* class insulation with high permissible temperatures is used in the primary coil of the transformer. As was described previously, there are also cooling fins between the high temperature sodium duct and the transformer, as well as a heat insulation plate made of thin aluminum between the secondary coil (copper plate) and the primary coil. Therefore, the temperature of the primary coil which presents an insulation problem can be kept low enough to provide sufficient insulation safety.

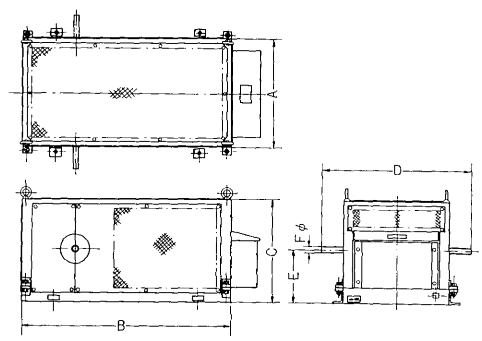
(3) Since leakage reactance is reduced by the fact that the primary and secondary transformer coils are wound concentrically on the same core leg, the pump is very efficient despite the fact that low voltages and high currents are used.

2. Pump Series

Table 3 lists the series and dimensions of the Fuji electromagnetic pumps.

Table 3 Fuji Electromagnetic Pump Series

Type		Ac Faraday		
Flow rate (l/min)		200	50 (40)	10 (6)
Head (kg/cm^2)		2	2	2
Fluid used		Liquid sodium		
Permissible fluid temperature (°C)		600		
Permissible pressure (kg/cm^2)		5		
Power supply		1 ϕ, 200 V, 50/60 Hz		
Input (kva)		30	5	4
Dimension (ca) mm	A	740	380	380
	B	1160	740	740
	C	640	410	410
	D	1040	680	680
	E	360	240	240
	Fϕ	42.7 (1¼″)	21.7 (½″)	17.3 (⅜″)



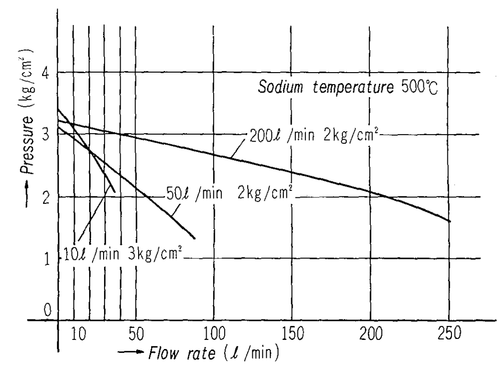


Fig. 9 Characteristics of Fuji electromagnetic pumps

V. TEST RESULTS

Test results for the various types of pump are shown in *Fig. 9*. The tests were carried out in the sodium test loops at Fuji Electric and at Japan Atomic Energy Research Institute.

Fig. 10 is a flow diagram of the test rig at Fuji Electric. As can be seen from this figure, this rig contains a special short loop as well as sodium pressure gauges in the inlet and outlet, and a flowmeter in the outlet. The flow is fixed by means of the adjustable valve in the outlet, *Fig. 11* is a photogragh of the test loop in use.

At present, enclosed channel detection test equipment ordered by Power Reactor and Neuclear Fuel Development Corporation is being manufactured. This equipment has been set up at Fuji Electric

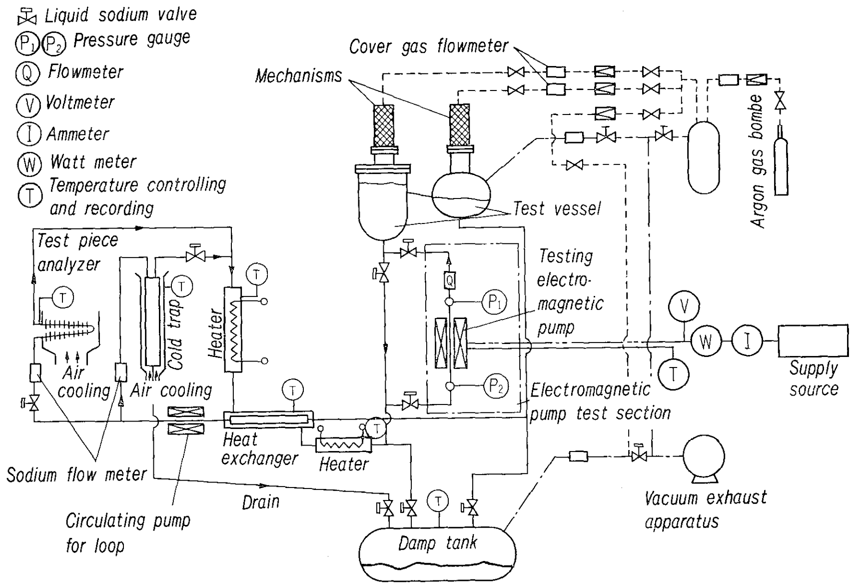


Fig. 10 Flow sheet of test rig for liquid sodium

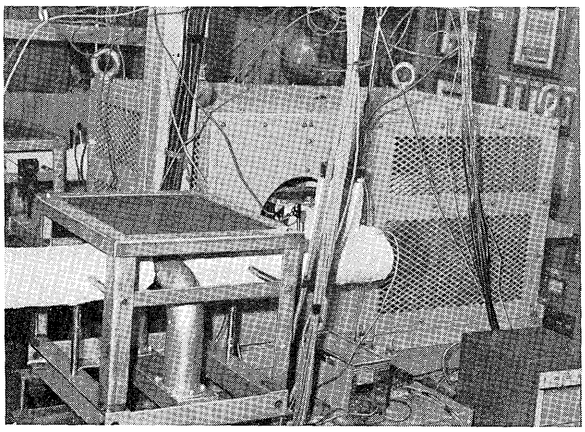


Fig. 11 Test conditions for sodium loop (200 *l*/min)

and makes possible the testing of 1000 *l*/min type electromagnetic pumps.

VI. CONCLUSION

The newly-developed Faraday series of electromagnetic pumps described above feature especially high reliability cover long periods and should meet all users' expectations. At present, 1000 *l*/min linear induction types pumps are being developed and plans are to enlarge the series to include capacities between 10 *l*/min and 1000 *l*/min.

The authors wish to thank Power Reactor and Neuclear Fuel Development Corpolation and Japan Atomic Energy Research Institute for their suggestions and the use of their test equipment, as well as Kawasaki Heavy Industries Ltd. for their help in the development of these pumps.

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