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LARGE SCALE SLUDGE FREEZING SEPARATION SYSTEM FOR WATER WORKS

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I. INTRODUCTION

In order to cope with the rapidly increasing amount of waste material laws concerning pollution control and environmental preservation are becoming increasingly severe, and social demands for pollution control equipment and for effective waste treatment methods are mounting. Such sludge as that discharged from industrial effluent treatment plants attached to water works, sewage disposal plants, and metal plating plants is also included in this category of waste material. Since these types of sludge are colloidal suspensions containing 90% or more water, in processing them, first of all, they must be dewatered to reduce their volume without causing secondary pollution. For example, in water works, sludge has conventionally been treated with sulfuric acid or lime and subsequently mechanically dewatered. Recently macromolecular coagulants are increasingly used for the same purpose, but since systems utilizing chemical agents are liable to cause secondary pollution, demand for new systems requiring no chemical agent are becoming increasingly urgent. With the increasing deterioration of rivers however, waste sludge is becoming higher in organic content so that most types of sludge are now very hard to filter and dewater; in fact, dewatering is so difficult that without chemical agents, they can hardly be dewatered with a mechanical vacuum filter, and are dewatered with a pressurized dewatering machine only at a greatly reduced efficiency. On the other hand, when sludge is once frozen and then thawed again, a physical change takes place in sludge; and, as the result, not only does the solid content become easily separatable from the liquid by conventional mechanical dewatering process but also, sometimes they separate even of themselve. Since the freezing separation process is capable of transforming sludge into a state in which it is up to one hundred times more easily filterable without the help of chemical agents, this process has come to attract the attention of those in related fields as being a very effective pretreatment method.

In these circumstances, since around two and half years ago, a sludge freezing separation system FSS lt/d has been marketed by Fuji Electric Co., Ltd., and in June 1974 a large scale sludge freezing separation system for water works was completed and one such system was installed by the company in the Ichinoide Municipal Water Works of Matsuyama City, which has been in service without any major trouble since. In the following chapters, an outline of the sludge freezing separation system is given and then the sludge treatment installation of the Matsuyama City Ichinoide Municipal Water Works is briefly described.

II. DEWATERING OF SLUDGE BY FREEZING AND THAWING

1. Principle of Dewatering

In colloidal sludge, water is present in such forms as free water, pore water, surface water, capillary water, and inclusion water, and the main problem is how to separate water in these various forms most effectively. Although in conventional dewatering treatment, surface water and inclusion water are hard to extract, when sludge is frozen, because solid particles become coarse and therefore the total surface area of the particles becomes less, the amount of surface water decreases, and inclusion water also becomes easily removable. *(Fig. 1)*

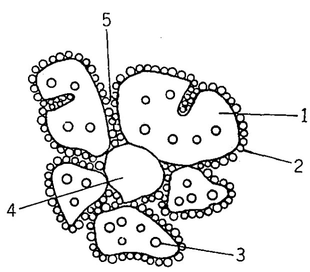


Fig. 1. Combination of sludge particles and water

When colloidal sludge, as schematically illustrated in *Fig. 2* (a), is cooled to below the freezing point of water, ice first starts to form at the cooling surface and then free water moves towards the newly formed ice to deposit on it in the form of ice. As ice grows in this way, the ice-water interface advances and pushes solid particles forward, which then become gradually concentrated on the ice-water interface. This is known as the macromoving mechanism. Simultaneously with this, another moving mechanism

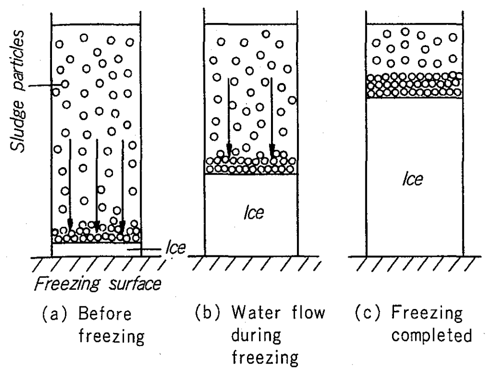


Fig. 2. Macromoving mechanism

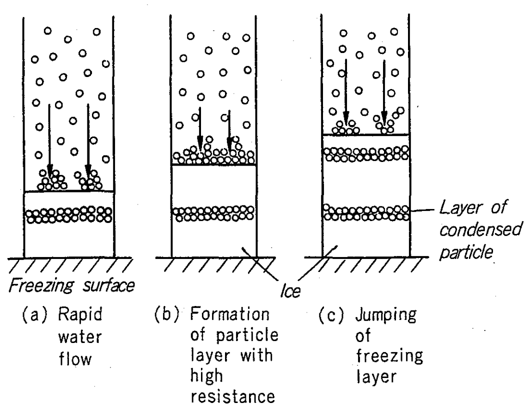


Fig. 3. Micromoving mechanism

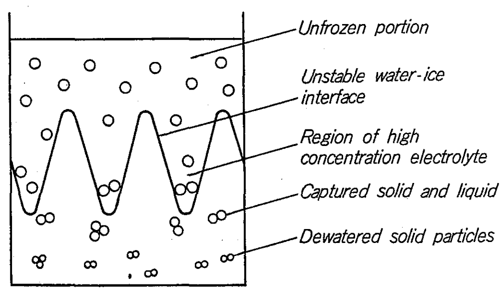


Fig. 4. Effects of condensed electrolyte on the freezing pattern

known as the micromoving mechanism, shown in *Fig.3*, also takes place to inhibit the flow of water to the freezing interface. Each time this happens the freezing interface jumps over the blocking layer of solid particles, so that a body of ice containing alternate layers of concentrated solid particles between layers of ice not containing solid particles is obtained. When sludge contains some dissolved salt, the ice-water interface advances irregularly as shown in *Fig. 4*, advancing further where the liquid phase freezes easier than other parts, to form an unstable ice-water interface, and the solute becomes trapped in ice in a supercooled condition.

In this process, groups of particles are deformed and broken up so that inclusion water becomes also removable.

When a frozen body thus formed is thawed, the solid material existing in the form of layers precipitates without changing its dewatered condition,and clear liquid phase

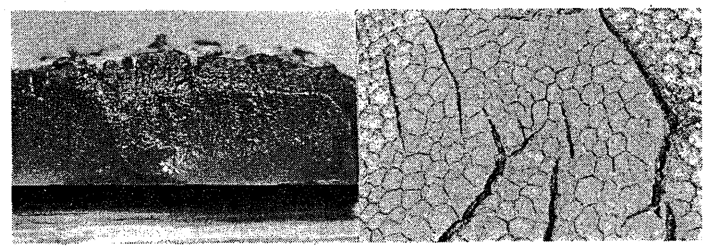
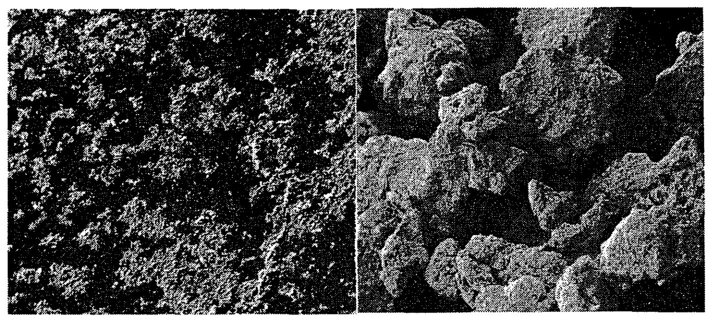


Fig. 5. Section and surface of freezed sludge



(a) Raw sludge, × 150 (b) After treatment, × 50

Fig. 6. Microphotograph of filtration plant sludge

appears above the bottom layer of precipitated solid material. In this condition, solid particles do not become colloidal again and, since they precipitate and are filtered up to several hundred times more quickly than before the treatment, low water content cakes are easily obtained through the gravity filtering process or with simple mechanical filtering equipment.

2. Freezing and Thawing of Sludge

Heat conduction problems involving such phase conversion as freezing and thawing are hard to analyze on account of the existence of latent heat, and the change of thermal characteristic values between the solid phase and liquid phase, so that normally approximate solutions or numerical solutions are all that are obtainable.

In an actual process of freezing sludge, unlike the case of pure ice, as the sludge is separated from the ice phase and becomes concentrated, colloid particles grow coarser, so that sludge concentration does not always take place uniformly and continuously as the freezing interface advances. As the growth rate of particle size is influenced by freezing speed, sometimes tightly grouped fine particles appear on the broken surfaces of the frozen sludge, but, in other times, particles are present in ice layers approx. 0.5 mm thick appearing like sprinkled sesame. *Figs. 5* and *6* show the surface, sectional view, raw sludge, and those particles grew coarse through freezing. The sludge layer was about 10 mm thick and was frozen from below.

There seems to be no report on the analysis of freezing and thawing phenomenon involving changes in the thermal characteristic values in sludge layers. In an industrial context, although this varies somewhat depending on the natures of the sludges and freezing speeds, up to a sludge concentration of approx. 10%, the freezing and thawing behaviors of sludge are not much different from those of pure water. With sludge of higher concentration, frozen by means of vertical freezing surfaces, as the sludge freeze and expands it pushes upward but in doing so the rising portion of the freezing surfaces. With sludge of low concentration, not much different from water in viscosity, the freezing sludge portion always wets the freezing surfaces as it rises upward, so that such sludge freezes quicker than more concentrated and more viscous sludge. However, sludge of high viscosity way also be made to freeze quicker to some extent when a small amount of water is poured on its surface or when separate arrangement is made to inject chilled air into it. In any case, sludge generally takes somewhat more time to freeze up to its top surface than water.

The time required for water to free its latent heat through pipe walls is expressed as follows:

$$Z = \frac{L}{2\lambda(-t_0)}(r^2 - r_0{}^2)\left[\frac{\lambda/r_0}{\alpha} - \frac{1}{2} + \frac{(r/r_0)^2 \ \ell n\,(r/r_0)}{(r/r_0)^2 - 1}\right]$$

where Z: time
- L: Amount of heat required to freeze $1m^3$ of water ($kcal/m^3$)
- t_0: Temperature of pipe (temperature of refrigerant)°C
- α: Thermal conductivity of refrigerant ($kcal/m^2 hr°C$)
- λ: Thermal conductivity of ice ($kcal/m^2 hr°C$)
- r_0: Radius of pipe (m)
- r: Radius of ice

The total freezing time is obtained when the time for the sludge to cool from ambient temperature to 0°C, the time for the ice to cool from 0°C to about –5°C, the time required for the upward bulging portion to freeze, and the time delay for the lower portions of the container to freeze are all added to the time calculated by the above formula.

In the case of thawing, because no further cooling is required after the moment when all the ice phase of the frozen mass of sludge is changed into liquid phase at 0°C, the heat requirement is less htan for freezign by the amount of heat equivalent to the sensible heat required for the liquid phase to warm to the ambient temperature. However, since in thawing heat transfer is generally slower than in freezing; thawing ordinarily takes more time than freezing; thawing ordinarily takes more time than freezing, but, in practice, this can be often compensated by an increased temperature gradient obtained by the utilization of the discharge heat of the freezing circuit.

Generally for freezing and thawing sludge, batch-by-batch type freezing-thawing tanks are used. These tanks are either cooled directly, with the tank itself forming the condenser and evaporator of a freezing circuit, or indirectly by brine.

In the latter system, brine, a liquid having a low freezing point like aqueous solution of calcium chloride, methanole, and propylene glycol, is cooled in an evaportaor and sent to the freezing tank; for thawing, brine is heated in a condenser and sent to the thawing tank.

Since these systems have both advantages and disadvantages, a system that is more advantageous for equipment of a certain capacity may be disadvantageous for other equipment of different capacity.

The FSS system installed in the Matsuyama City Municipal Water Works is an indirect cooling system using an aqueous solution of calcium chloride as the refrigerant.

III. SLUDGE TREATMENT INSTALLATION IN MATSUYAMA MUNICIPAL WATER WORKS

1. Plan

The sludge treatment installation in the Matsuyama Municipal Water Works is the first such system in Japan. It was designed to process water works sludge based on the freezing separation principle and aimed at obtaining cakes containing 55% or less water without using chemical agents.

In selecting a sludge processing system, the following requirements were weighed carefully; as the result, the freezing separation system was adopted.

1) Because the proposed installation is for eliminating pollution, it should not cause any secondary pollution.

2) The proposed installation should be able to function properly even when the raw water will be putrefied or will contain much organic matter through plankton, etc., in the future.

3) The dewatered cakes should be obtained with a water content below 55%, and in conditions not harmful as reclamation soil.

4) The water obtained from the installation by filtration and as the top water should be good enough to be re-used to meet the requirement for effective utilization of water resources.

5) The system should have low construction and maintenance costs, and be easy to operate.

The Ichinoide Water Works is an important one for Matsuyama City, processing a daily maximum of $99{,}000m^3$ of raw water through chemical precipitation processes and rapid filtration processes, supplying a major part of the utility water demand of the city with its supply capacity of $92{,}000m^3$.

The average turbidity of the raw water of this water works throughout the year is 20 degrees with the peak turbidity in summer reaching 120 degrees. The water works operates at an overall aluminum sulfate infusion ratio of 20 ppm. The new sludge processing plant has been planned to recover 2.54 tons of dried cake daily, operating 6 hours per day and 6 days per week. The planned treatment capacity of the new plant is shown in *Table 1*.

A balance chart of this sludge treatment plant has been made on the basis of the basic data shown in *Table 1*, and is shown in *Fig. 7*. According to this balance chart,

1) The sludge accumulated in the sedimentation basin is temporarily stored in a sludge discharge basin, and then

Table 1. Plan capacity

Raw water:	Quantity	99,000m^3/d
	Turbidity	20 degree (average)
	Aluminum sulfate infusion ratio	20ppm
Sedimentation basin water delivery rate		1,800m^3/d
Filter basin water delivery rate		3,300m^3/d
Cake:	Water content	Below 55%
	Dried solid matter	2.54t/d
Quantity of re-used water		5,000m^3/d (Filtered water and top water)
Concentration of treated sludge		Approx. 17%
Operating time		6 hours/day (6 days/week)

pumped into a thickner.

2) In the thickner, after 24 hours of plain (gravity) sedimentation, the sludge is concentrated to about 2% and is then pumped into a centrifugal separator via a sludge feeding basin.

3) In the centrifugal separator, sludge is further condensed (secondary condensation) to approximately 17%, and then, the condensed sludge is temporarily stored in a sludge storage tank to be later sent to a freezing-thawing tank by a sludge pump.

4) In the freezing-thawing tank, sludge is frozen for two hours and thawed for two hours.

5) The sludge taken out of the freezing-thawing tank is dewatered in a vacuum filter to a water content of less than 55% and is then sent to a cake hopper by a belt conveyor. The sludge is intermittently extracted from the cake hopper to be trucked away.

6) The wash discharge water of the filter basin is stored temporarily in a waste water basin and then pumped back together with the top layer water of the thickener and other units to the receiving basin to be reused.

Individual units were designed according to the balance chart given in *Fig. 7*, and the flow chart shown in *Fig. 8* and the specification list of *Table 2* were obtained.

2. Outline of Individual Units

1) Building and layout

As the plant is located in the neighborhood of a residential area, due consideration was given to the abatement of noise from various units, particularly from the centifugal separator and the refrigerating machine. All the units developing noise were arranged farthest from the residential area and were not only installed in a building having sound-proof walls, but also their foundations were separated from the foundations of the building. The cooling tower and the air conditioning units were installed on the second floor at the side farthest from the residential area; all other units were installed within sound-proof enclosures. The arrangement of the entire sludge treatment installation is shown in *Fig. 9.*

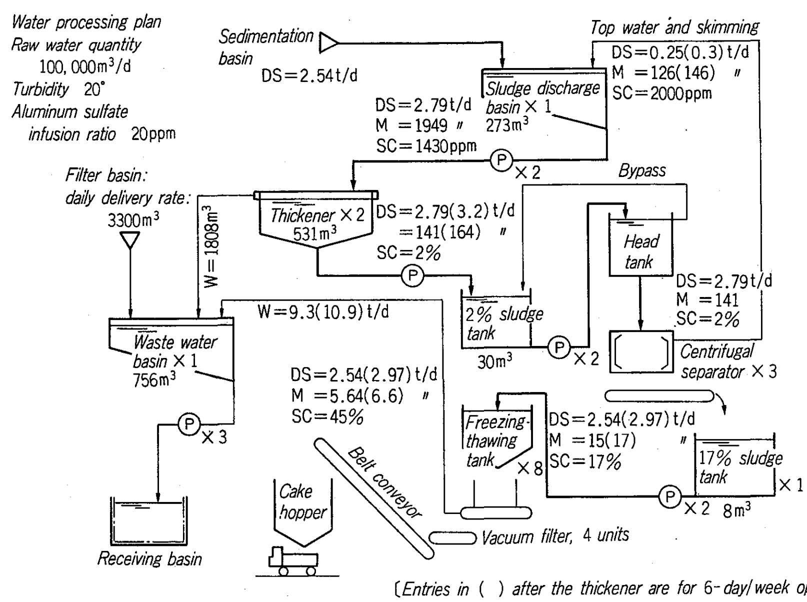
2) Mechanical concentration

As it is very uneconomical to freeze a large volume of low concentration sludge, the sludge is first mechanically dewatered to a maximum level suitable for freezing separation to reduce the refrigeration load to a lowest possible limit. For this mechanical dewatering process, after extensive experiments, a centrifugal separator was adopted. This machine, based on the vertical skimming principle, is designed to process sludge for 15 to 20 minutes per batch, and then to discharge concentrated sludge. The discharged sludge is temporarily collected in a blender by means of a raking machine to be made uniform in concentration, and then pumped to the sludge tank.

3) Refrigeration plant and brine system

As shown in the flow chart of *Fig. 8*, the refrigeration circuit comprises two systems, each including four freezing tanks. The refrigerating machines are screw type units that allow continuous capacity adjustment.

The condenser unit is divided into two parts, the primary condenser being cooled by water, and the secondary condenser being designed to heat hot brine employed to thaw frozen sludge. In this arrangement, the



〔Entries in ( ) after the thickener are for 6-day/week operation〕

Fig. 7. Balance chart

Table 2. Plant specifications

	Sludge processing capacity		72t/d
	Thickener: Capacity No. of units		$531m^3$ x 2
	Sludge feeding basin: Capacity No. of units		$30m^3$ x 1
	Compressor type No. of units		Screw type, 2 units
	Freezing capacity		76JRT
Refrigerating machine			(TE = 20°C, TC = 35°C)
	Compressor motor	Type	3 phase, squirrel cage induction motor
		Rated output	160kW
	Brine cooler	Dia. x length	711φ x 3,100L
	Primary condenser	″ ″	690φ x 2,850L
	Secondary condenser	″ ″	580φ x 2,850L
	Refrigerant		R-22
	Cooling tower	Cooling water flow rate	$75m^3/h$
	Freezing-thawing tank	Material	Steel plate
		Capacity x No. of units	$1.5m^3$ x 8
	Centrifugal separator	Sludge discharge capacity x No. of units	350ℓ x 3
		Centrifugal force	1,300G
	Vacuum filter	Filter area x No. of units	$2m^3$ x 4
		Degree of vacuum	500mmHg
	Cake hopper		$23m^3$

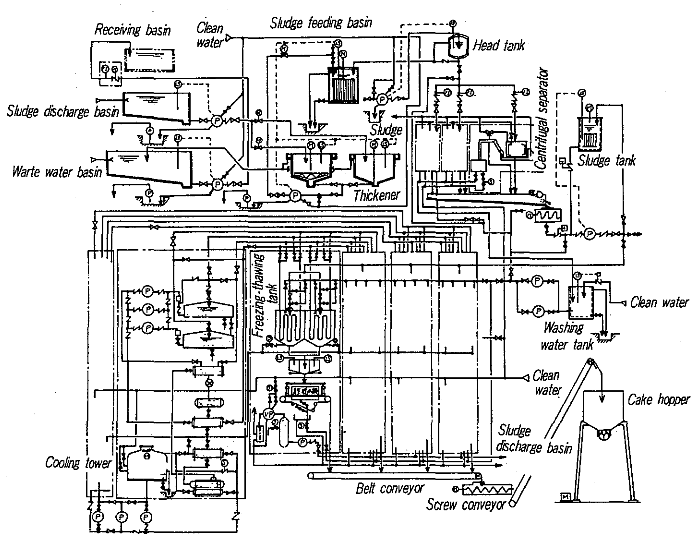


Fig. 8. Flow chart

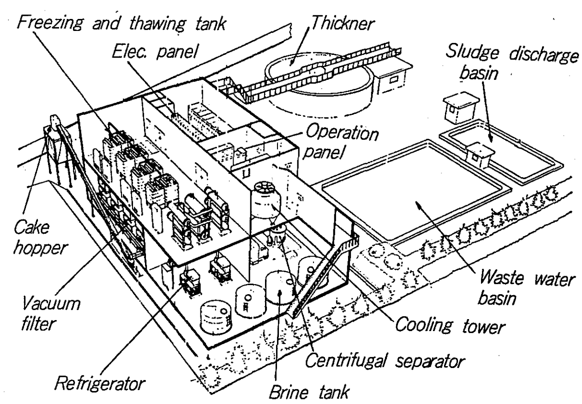


Fig. 9. Sludge treatment installation layout at Matsuyama City Ichinoide Municipal Water Works

flow rate of the primary condenser cooling water is so controlled as to maintain the temperature of the hot brine at a predetermined level. The cooling water is cooled in the cooling tower, the fan of which is either operated or stopped to compensate for the seasonal fluctuation of ambient temperature.

The brine system is divided into two circuits, of which one is the freezing circuit and the other is the thawing circuit. In the freezing circuit, brine is pumped from the brine tank through the brine cooler to be cooled and become chill brine, then into the freezing thawing tanks. In the thawing circuit, brine is pumped from the hot brine tank through the secondary condenser (brine heater), to be heated and become hot brine, then into the freezing-thawing tanks. In both the freezing and thawing phases, the thermal load is high during a short period in the beginning so that thermal load fluctuates continuously at certain intervals. The tank capacity serves to absorb this fluctuation and therby to prevent overloading the compressor.

4) Freezing-thawing tank

In designing the freezing-thawing tanks of the present installation, a series of developmental tests were conducted and the experiences of the previously completed FSS 1t/d machine were carefully studied. On the basis of the prerequisite conditions that freezing and thawing should be completed respectively within two hours, all such details as the arrangement of the freezing-thawing heat conducting surfaces, freezing-thawing time delay within the tanks, relieving of volume expansion during freezing, stress analysis of the heat conducting surfaces, thermal stress analysis of the heat conducting surfaces between the freezing time and the thawing time, removal of precipitated and separated sludge during the thawing stage, and uniform filling of the tanks with sludge were carefully examined.

The main constructional features of the tanks are as follows.

(1) The tanks were designed as a nearly cubical box, with the bottom inclined at approximately 45°
(2) The tanks were designed in such a way that stress was evently distributed and that even when sludge was closed at the bottom, the tanks can withstand the pressure. Provision has been made to discharge sludge when excessive pressure develops inside to relieve the pressure.
(3) In order to satisfy the requirements of convenient sludge filling, discharging, and cost reduction, the heat conducting surfaces were designed as vertical square-arranged multiple tubes which were supported both vertically and horizontally.
(4) The tanks were internally lined with elastic insulating material covered with thin rubber film. In order to provide the function of distributing freezing stress in addition to the insulating function, the thickness of the insulating material was varied from portion to portion.
(5) The header of the group of tubes was divided into several parts to facilitate dismantling, and the tubes were staggered by one pitch.
(6) In order to shorten thawing time, an arrangement was made to inject hot water from the bottom into the tanks.

The outside view of the freezing-thawing tanks is shown in *Fig. 10.* As can be seen here, in order to fill the tanks uniformly with sludge, several filling pipes are arranged from above into the tanks. There is also a provision for injecting washing water towards the tank walls after discharging sludge. The effective capacity of the tanks is $1.5m^3$.

5) Dewatering devices

The adopted vacuum filter has a filltering area of $2m^2$ per unit. Sludge is dropped on the filtering cloth (Saran cloth: 3001), and vacuum produced by a water-sealed vacuum pump is applied at the bottom of this filter cloth to dewater the sludge. For the purpose of effectively utilizing the filter area, three dewatering processes were designed per two-hour operation cycle time; and, for this, sludge discharged from the freezing-thawing tanks is divided into three parts in the intermediary hopper.

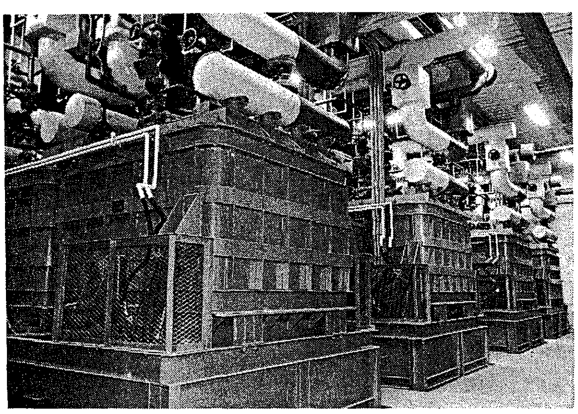


Fig. 10. Freezing-thawing tank

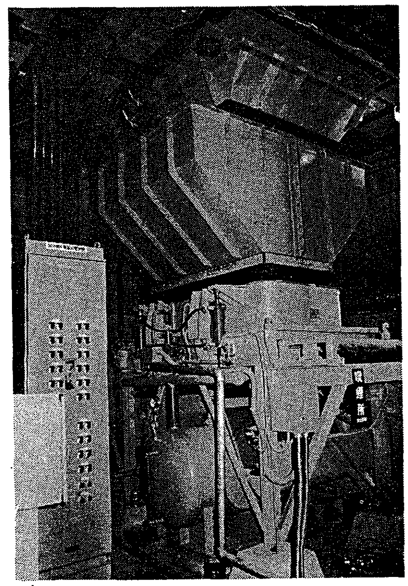


Fig. 11. Vacuum filter

6) Control

The control panel comprises all units required to control the operation of the entire set of sludge treatment units including a 6.6V service entrance switch board, a transformer (6.6/0.4kV, 6.6/3.3kV), a refrigerating machine reactor starter, a control center, a graphic operation display panel, a d-c power supply switchboard, a universal sequencer USC-4000, a solenoid valve power supply board, and a field control panel. All of the processes are grouped into five blocks: the primary condensing cycle, the secondary condensing cycle, freezing-thawing cycle, the dewatering cycle, and ejecting cycle, with one block internal control master switch incorporated in each block control circuit. These master switches and the main master switch that control the sequencial operation of individual cycles cooperate to control the automatic operation of the entire plant. The sequence of operation is monitored by the graphic operation display panel, and when the power supply fails the operation conditions at the moment of power stoppage are kept until power recovery on the graphic operation display panel which is served by a d-c source during the power stoppage.

3. Performance Record

1) Operation

The entire installation operates, system by system, fully automatically. The refrigerating machines are first warmed up for a certain time and chilling brine is cooled to -15°C or below; then a freezing phase is started. According to the sequential automatic operation schedule, sludge is poured into the tank, a freezing process is started and after two hours the freezing process ends and a thawing process

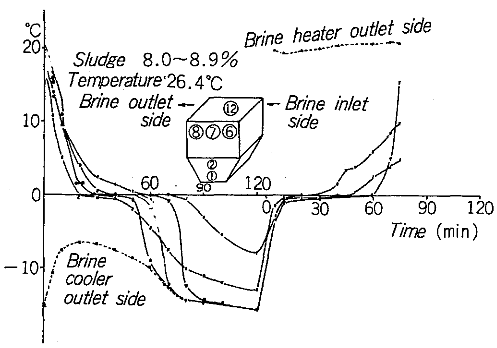


Fig. 12. Freezing-thawing time curves

is started. During the thawing process, after the lapse of a preset time, water is poured into the tanks to acclerate thawing. As sludge thaws after the lapse of a preset time, the discharge gates are opened to discharge sludge and, at the same time, flushing water is injected to wash the inside of the tanks. The gate is then closed again to bring the tank to the initial condition.

2) *Fig. 12* shows the trend of sludge temperature in the tank and the brine temperature. Thermal load is large in the initial stage of the freezing cycle, so that the compressor operates at its full capacity, but towards the end it drops sharply. As a freezing stage is started with the brine cooled to -15°C during the freezing stage, brine temperature rises temporarily but then cooling is again effected in accordance with the freezing load to bring the temperature back to the initial level. The brine temperature change trend is influenced by the initial brine temperature, the extent of load change, brine tank capacity, and brine circulation quantity. Although between the brine outlet side and inlet side, and between the upper part and the lower part of the tank, freezing time differs slightly, the sludge is totally frozen after two hours. With the help of water poured into the tanks during the thawing process, the whole frozen sludge can also be completely thawed within two hours.

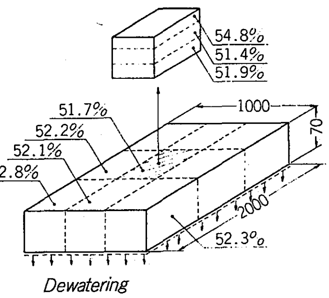


Fig. 13. Distribution of water content

3) Water content of cake

The measured values of water content of the cakes made in the vacuum filter are shown in Table 3. The water content of the cakes produced in the vacuum filter while the sludge treatment installation is automatically operated ranges between 50 and 55% satisfying the planned performance conditions. The distribution of cake water content across the 1m x 2m filtering surface is shown in *Fig. 13*. Vertical water content distribution is also shown in *Fig. 13*, indicating a slight increase of water content towards the top surface. This is because of the fineness of sludge particles constituting these cakes.

4) Required power consumption

The change in the compressor power consumption during one freez-thaw cycle is shown in *Fig. 14*. *Table 3* shows the electric power consumption data in automatic operation. According to this table, in automatic operation, the compressor consumes between 50 and 55kWh of power per ton of sludge.

Table 3. Some examples of test result

Date	Tank No.	Water content (%)	Sludge concent-ration (%)	Cake thick-ness (mm)	Vacuum (mm Hg)	Refrige-rator motor mean input (kW)	Power consump-tion per ton of sludge (kWh)	Remarks
6/27	1-1	53.1	6.7	30	–	83.4	55.6	Automatic operation
	1-3	52.4	〃	39	–			
	2-1	55.0	〃	25	–	80.6	53.7	
	1-4	52.4	〃	29	–			
6/28	1-2	53.2	8	37	500	78.7	52.5	
	1-4	51.6	〃	38	580			
	2-1	52.3	〃	33	–	75.0	50	
	2-4	55.3	〃	54	–			
6/30	1-2	55.0	10.6	80	–	–	–	
	1-4	51.8	〃	70	–			
	2-2	54.0	11.8	45	200	78.0	52	
	2-3	54.3	〃	47	130			
	2-2	52.0	10.6	73	–	–	–	
	2-3	52.7	〃	69	–			

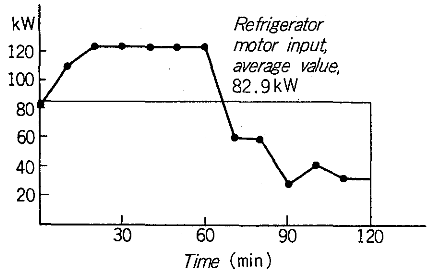


Fig. 14. Change of compresser power

5) Noise

The noise abatement measures adopted proved to be very effective, and the noise level outside the building was maintained at a level below 50 phon.

IV. CONCLUSION

A brief description of the large scale freezing separation system for water works and its performance record have been given. The freezing separation process is known to have great advantages over other processes, so that the installation at the Ichinoide Municipal Water Works in Matsuyama City has been attracting the attention of many prospective users since its inauguration.

In addition to the present installation, orders for further large scale freezing separation installations for sludge treatment have been received from the Mie Prefectural Project Agency, Chiba Prefectural Water Bureau, and Chiba Prefectural Project Agency, and they are now under fabrication.

In closing this report, the authors should like to express their sincere sense of appreciation for the valuable cooperation given by the Matsuyama City Municipal Project Bureau.

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