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Experimental Study of LNG Underground Tank

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Our operating experiences for six years have proven success of LNG underground storage tank (UGT). The UGT has inherent safety, which is aspired in Japan, where a big earthquake is apt to occur, and the space for construction is limited. This paper relates to significant problems particular to low temperature of the UGT, referring to soil, reinforced concrete insulation, sealing membrane, etc. The behavior, at low temperature based on the experiences and researches, is also described herein.

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INTRODUCTION

This paper relates to the outline of the LNG underground storage tank and experimental studies thereof.

The UGT has been successfully developed by Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) in Japan, in cooperation with Tokyo Gas Co., Ltd.

Introduction of LNG made it possible to avoid air pollution, but social concern is focussed to the requirement that adequate safety measures should be taken in mass storage facilities for LNG, since there have been several recent experiences with leakage of inflammables in Japan. That is, tank structure must be well considered to prevention of possible secondary disaster in the case of unforeseen events such as big earthquake, crash by flying objects and others.

The basic conditions required for the UGT are as follows:

- Container should be of perfect sealing for a long time, to keep LNG safely
- Heat flux due to the temperature difference between LNG and the surrounding should be surely controlled within the predetermined value
- Initial investment and maintenance cost should be competitive with conventional metallic above ground tanks
- Easy maintenance

A lot of trials to solve difficult problems and to meet the aforementioned requirement had been made for several years, and we reached the conclusion, this type of UGT which is of steel dome roof and reinforced concrete cylindrical wall with sealing membrane and insulation.

This paper covers some of the important researches and results, as itemized in the following;

- External forces to the structure of UGT
- Physical properties of soil at low temperature
- Required conditions of insultion materials
- Establishment of thermal calculation system
- Establishment of sealing system.

OUTLINE OF UGT

The system developed and constructed by IHI and Tokyo Gas provides for an inner tank, the loads on which are transmitted to a cylindrical reinforced concrete through the insulation suitable to withstand pressure forces. The most significant feature in this design is that the contact between inner tank (membrane), insulation and supporting outer jacket (concrete wall) is maintained during all conditions of operation.

The tank is closed at the top by means of a steel roof having the shape of dome. The roof supports a suspended ceiling, on which the insulation of the roof is applied.

In principle, with this type of design, the cylindrical part of the tank is almost entirely located below the ground level. In case the soil conditions are not suitable for UGT from a cost and/or technical point of view, to be sunk so as to keep the maximum liquid level below the top of the ground level, the more favorable solution to be adopted for arrangement of the tanks below ground-level will be such that the tanks will be sunk by its appropriate portion below the ground level, and the remainder is achieved by raising the ground.

Consequently, the principle of the IHI underground tank is maintained, even if details require to be changed.

Fig. 1 shows a schematic drawing of the UGT.

Roof

The roof is of a steel plate type dome with a compression ring attached. Insulation is placed above the aluminum suspended ceiling, and the external roof is of mild steel; however, the side plates must be of materials selected for their

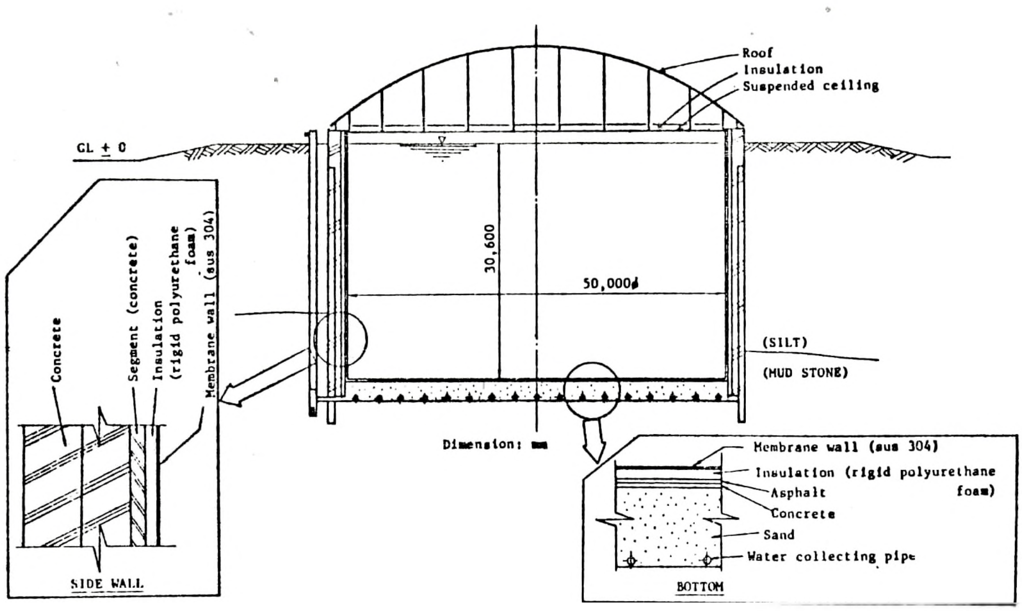

Fig. 1 60,000 kl LNG underground tank

suitability for thermal conditions.

The roof load is calculated based on the weight of the roof including the piping supported by the roof, piled snow load, live load, wind load and internal pressure.

Membrane

The material for the membrane is SUS304. If its structure can react sufficiently for heat expansion, and the liquid sealing function is sufficient, any form can be employed. In this tank, double corrugated membrane is mainly applied.

Insulation

Polyurethane foam is used in the sides and bottom of the tank, while mineral glass wool is used in the roof section. The design calls for evaporation less than 0.2 percent per day. The heat input to the UGT tends to reduce with time; therefore, the tank is designed so that the foregoing value is satisfied one month after start of operation.

Shell Structure

The side wall is a cylindrical reinforced concrete structure with composite shell segment inside. Segments have been used in the construction of tunnels and similar projects. In its application to the UGT, insulating materials and membrane are attached to the composite segments.

Bottom

Several types of bottom have been adopted for UGT. The type of bottom depends on the soil condition. If the soil condition is so rigid as rock or mud stone, such soils will be used as tank bottom. In feeble soil, concrete bottom is usually adopted.

FROZEN SOIL

The soil surrounding UGT extends its frozen length unstably as time goes on. The frozen soil produces alternation of physical properties, which are most subjected to water in soil and freezing speed. So the soil freezing phenomena will be very difficult problem to solve theoretically. It will be necessary to utilize historical records or to make test of soils for the planning of UGT. At the UGT, the freezing is developed from the surface of wall to the outerward and accompanied with the expansion of soil. In the earth, the expansion of frozen soil will be limited by the surrounding soil and, consequently, the reaction force against the wall will grow.

In our experiences and tests, it is confirmed that the freezing pressure grows, as soil freezing increases, and reaches its maximum. After passing the maximum point, the freezing pressure saturates for one case and decreases for another case.

Shrinkage and creeping phenomena of soil will have great influence on the latter case. In any case, freezing pressure should be decided by tests, unless data thereof are available. According to our research, feeble soils such as

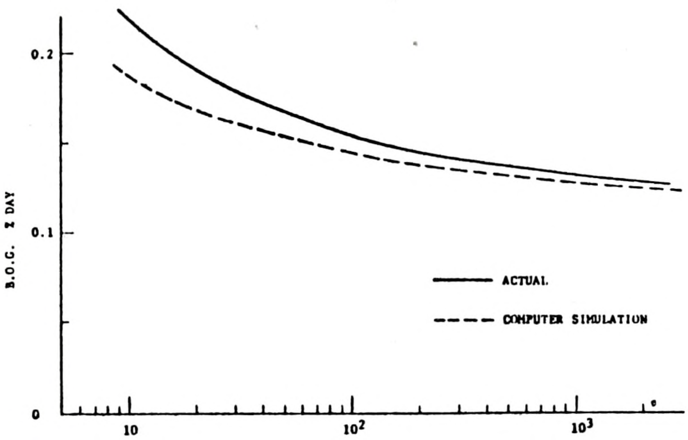

Fig. 2 10,000 kl LNG UGT boil-off gas ratio

silt have small freezing pressure, while hard soils such as mud stone are higher. Of course, sand or gravel will have no problem.

<u>Frost Heave</u>

As aforesaid, frost heave is generated by the expansion of frozen soil. So it is related with freezing depth and restriction by surrounding soil. If we allow heave to grow, freezing pressure will be decreased accordingly.

In our experiences, the frost heave of the existing tanks is about 2 ~ 4 percent of length of frozen soil, but effect of restrictive force against the frost heave is not so clear. Generally speaking, consideration should be paid to piping and its foundation around the frozen type UGT to avoid the influence by the frost heave.

<u>Freezing Speed</u>

The freezing speed of soil is affected by soil condition, thickness of insulation materials, movement of underground water, etc. So it will not always be expected to have same thickness of frozen soil on all of the surface. Our experiences show that the tide of sea water is influential.

CONCRETE WALL

Reinforced concrete (RC) cylindrical wall forms the structure of UGT. In designing the RC wall, several kinds of external forces should be examined carefully.

The main points are as follows;

- Dead weight including roof weight
- Liquid and gas pressure
- Earth pressure

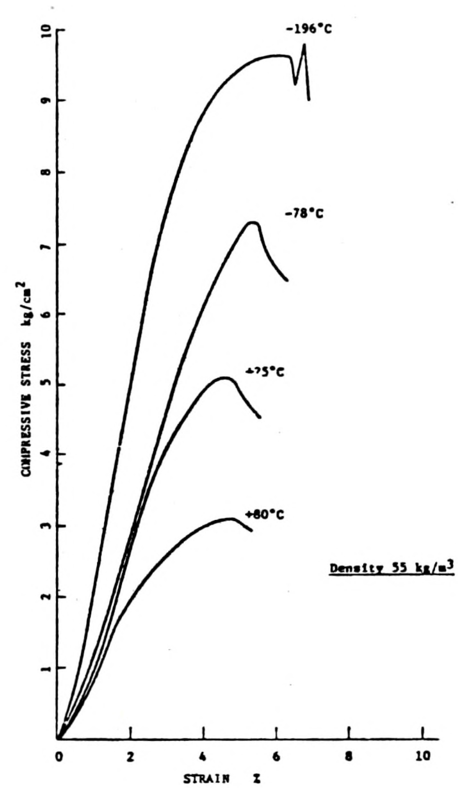

Fig. 3 Thid shows stress-strain curve of polyurethane due to temperature. Load is added to the direction parallel to foam formation

Seismic force acting against the underground structure is normally believed to be less than that upon the structure built aboveground. Same static seismic factor as that for aboveground tank is adopted for UGT.

<u>Unbalanced Earth Pressure</u>

In case the soils are geologically not uniform, that is, there are some different types of soils partially and the layers of soil are inclinated, the unbalanced earth pressure should be taken into consideration.

<u>Freezing Pressure</u>

Details are mentioned in the item for frozen soil.

<u>Thermal Stress</u>

Thermal stress upon the concrete wall will vary depending upon the form of structure and the distribution of temperature. In other words, it is concerned with restrictive force against the thermal stress produced by temperature gradient.

Naturally, earth pressure and/or water pressure load against RC wall will produce com-

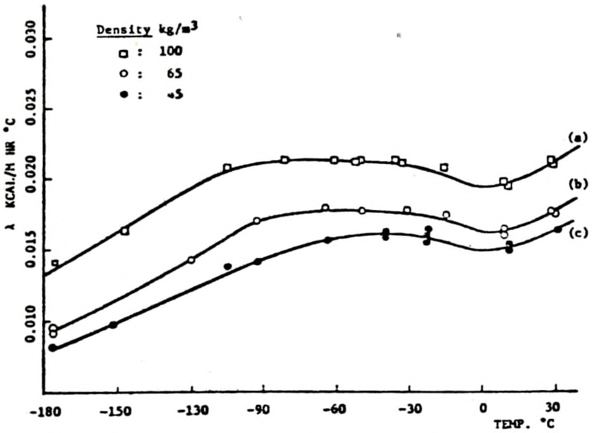

Fig. 4 This is a relation between conductivity and temperature of polyurethane foam

pression stress on any part of side wall. These loads will offset the thermal stress to some extent.

When the structure is to start cooling down from the inside of wall, tensile stress generates on the inside, and compression stress on the outside. These stresses are proportionally increased according to the amount of temperature difference between the two sides, on condition that the temperature is lineal across the thickness of RC wall, and not concerned with the thickness. This thermal force is connected with selection of the thickness of insulation materials.

In our design, the temperature should be kept within about 20 C at maximum. The thermal stress on the concrete wall reaches its maximum in about half a year after cooling down operation. From experiences, there was no case which caused even any fine crack on the tensile side of cylindrical R.C. wall.

HEAT CALCULATION SYSTEM

There will be no problem for commercial purpose in calculating heat flow of UGT which is surrounded by heating system, even with use of ordinary calculation methods.

In case of frozen type UGT, it is not easy to calculate the heat flow, because the progression of freezing front of soil around UGT changes the overall heat transfer coefficient every minute of time.

For this reason, a computerized analytical calculation method was developed. This is named "numerical analysis on free surface heat transfer problem having two dimensions and four layers." In this method, water movement to frozen soil, latent heat of water, and interference between two UGTs are also dealt with. The predicted performance made by the program is related to Fig. 2.

INSULATION SYSTEM

It will be clear that the insulating performance in low temperature storage system is one of the most important subjects to store substance safely and economically. So it is very important to predict the actual value by the predetermined method.

In case the actual heat flux into the reservoir exceeds the predicted value, the boil-off gas will be increased accordingly, and it brings trouble to boil-off gas treatment system and accelerates freezing speed of the surrounding soil.

The insulation effectiveness for the UGT (this will be increased as time goes on), is attained from insulation materials, concrete and soil surrounding UGT.

Of course, a majority of insulation effectiveness depends on the insulation materials, and soil, etc., affect slowly on heat flux. So the selection of insulation materials for UGT is very important, then a lot of research and tests are necessary prior to selection. The required properties to the insulation materials are as follows;

- Thermal conductivity, λ, should be lower, and λ/cost is the lower the better.
- It must have enough strength to bear internal pressure through the membrane, and to transmit it to outer wall without any undesirable deformation.
- Anti-water absorption material is preferred. There seems to be some water seepage through the outer concrete wall, or rain water during construction. When the insulation materials absorb any water, the insulation effectiveness is deteriorated.
- Any crack due to excessive contraction deteriorates insulation effect.
- It is desirable to use non-inflammable materials.
- Easy processing in fabrication and erection is a great advantage. With a lot of test and evaluation made on the foregoing subject, we reached the conclusion to adopt hard polyurethane foam (PUF), except for mineral glass wool on the suspended ceiling. The PUF is the most popular low temperature insulation material and is used in natural gas liquefaction plant or LNG piping.

The weak point of PUF will be that it is not non-inflammable and has higher contraction.

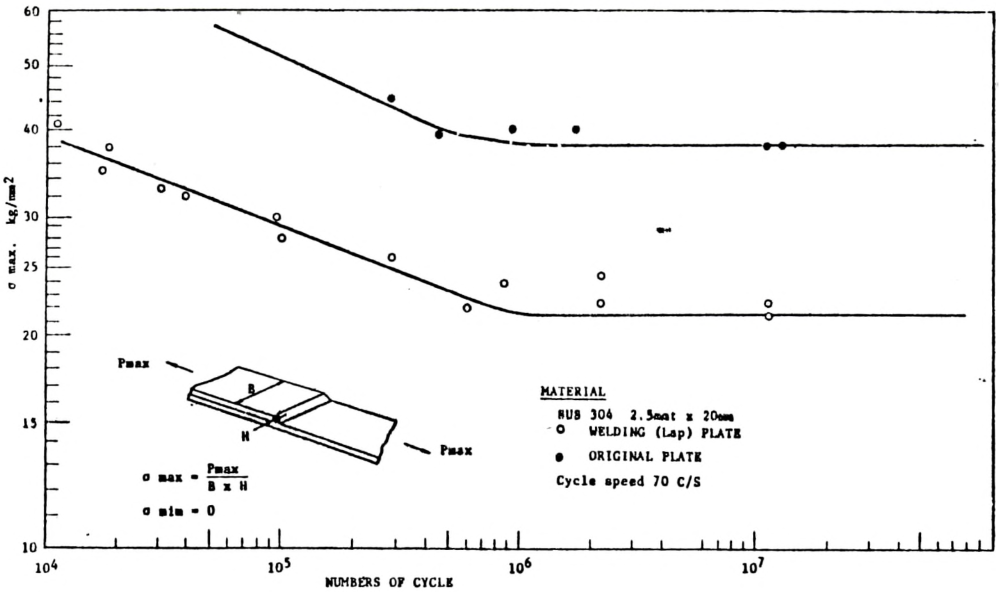

Fig. 5 This is a result of fatigue tensile test

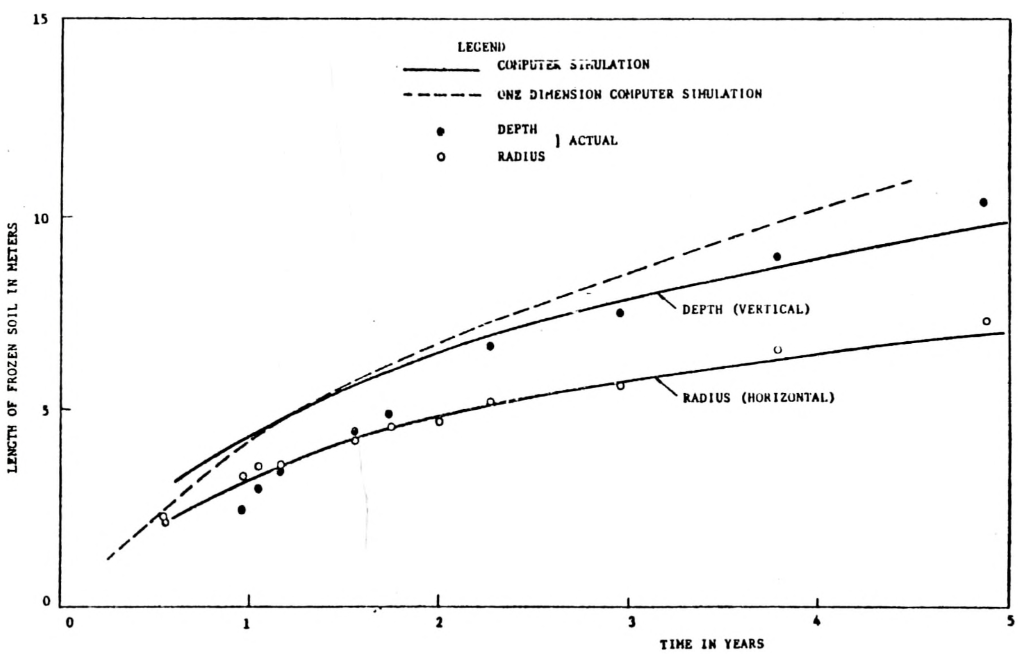

Fig. 6 Computer shows its accuracy. Dotted line is the simulation of one dimension analysis

Some of the physical properties of PUF, which are connected with UGT as insulation or structure part, are shown in the following:

Stress-Strain

Insulation material is pressed during the storage by internal pressure generated by liquid weight and vapor pressure, and the material yields shrinkage to some extent. So it is necessary to keep the shrinkage within a predetermined allowable value to prevent deformation of membrane.

The amount of shrinkage depends on the density and temperature. Details are shown in Fig. 3.

The coefficient of thermal expansion is also affected by the density and not always lineal.

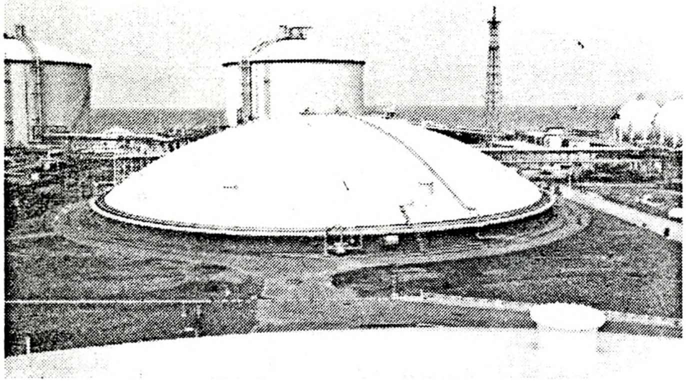

Fig. 7

Table 1 Manufacturing Records of IHI's Underground Tanks

Owner & Location	Capacity KL	Dimensions Diam x Ht M	No. of Tanks	Storage	Year Built	Remarks
Tokyo Gas Negishi Work	10,000	30 x 14.2	1	LNG	1970	
"	60,000	53 x 30.6	1	"	1972	
Tokyo Gas Sodegaura Work	60,000	60 x 21.2	2	"	1974	Bottom Heating
Osaka Gas Senboku Work	45,000	54 x 19.7	1	"	1975	Bottom Heating
Tokyo Gas Sodegaura Work	60,000	64 x 18.7	5	"	1976	
"	62,000	64 x 19.3	1	"	1977	
Tokyo Gas Negishi Work	95,000	64 x 31.1	1	"	1977	
"	95,000	64 x 31.1	1	"	1978	

Thermal Conductivity

Thermal conductivity of PUF is changed according to density and temperature.

Fig. 4 shows this relationship. From heat flux point of view, lighter material is preferable.

Determination of the value of thermal conductivity of insulation material should be mainly based on the test result at laboratory. In our experiences, conductivity of insulation materials attached to the UGT is inferior to the testing result by about 10 percent. This inferiority seems to come from the fine gap of each insulation panel or erection technique.

SEALING MATERIALS

As sealing materials, membrane should be given a lot of consideration and research. The materials should be superior in low temperature properties, fabrication processing, cost, etc. The materials taken into consideration were austenite stainless steel, invar (36 percent Ni steel), and aluminum alloy. Invar is excellent in its low contraction, but very expensive. Aluminum alloy has some problem in erection procedure and softness.

Austenite stainless steel is superior in welding procedure and elasticity in all actual temperature range and its cost will be reasonable. Type 304 stainless steel is considered to be suitable for use with UGT. If the membrane is concerned only with sealing, strength of membrane will be not so important but, actually, there is considerable amount of stress on some parts of membrane due to LNG pressure and thermal contraction. In this connection, reliable welding procedure requires adequate thickness of material. We have had several cases in selecting the thickness from 1 to 2.5 mm, and experiences prove it most reasonable to use 2 mm ~ 2.5 mm.

Tig welding procedure is adopted for lap and butt welding. This is performed by automatic apparatus and manual operation.

As mentioned in the foregoing, stress due to LNG pressure and thermal strain acts upon the welded parts and, furthermore, cyclic load generated by liquid filling and pumping out is added. So the welding procedure is very important for membrane.

As to the cyclic load, total cycle for 30 years reaches 720 cycles, when the cyclic load is estimated two times a month, so it is necessary to test fatigue phenomena. Fig. 5 shows the test results of the tensile fatigue stress in original plate and welding plate of membrane.

The membrane of tank is of flexible corrugation vertically and/or horizontally prepared to absorb thermal contraction. The number of corrugation is to be based on the fatigue test.

OPERATIONAL HISTORY

The operational results of UGT are as expected and some of the interesting results are described as follows:

Freezing

Fig. 6 shows the freezing depth at the middle of side wall and the center of bottom on the proto 10,000 KL LNG UGT. In this graph, the depth of frozen soil is 7 and 10 m, respectively, after five full years' operation. The average freezing speed for five years is 0.16 mm/hr at the middle of side wall and 0.22 mm/hr at the center of bottom.

There is some difference (about 3 m at maximum) in the length of frozen soil to the radius direction. Such difference will be caused by tide of seawater, because the length of frozen soil at the sea side of UGT is shorter than that of the reverse side.

Due to frozen soil, small crack and deformation on the surface of ground were observed, and frost heave phenomenon was also observed. But the foregoing factors could not be a trouble for maintenance.

Boil-Off Gas

Amount of boil-off gas is decreased with time, because the frozen soil will become a part of insulation. The operational records prove that all of the existing tanks have boil-off gas ratio of 0.15 ~ 0.1 percent/day, nearly equal to the estimation by thermal calculation system. Only one problem concerning the boil-off gas is that it exceeded the amount of the calculation a little at the beginning of operation in the 10,000 KL UGT. We reached the conclusion that some seepage from the side wall caused greatly such excessive boil-off gas.

Initial Starting Up

After dehumidification and air purging by nitrogen gas, cooling down of UGT is carried out by spraying liquid state LNG directly from the spray nozzles at the ceiling. This procedure is completed within two days, as the temperature decreasing gradient of membrane is controlled at 5 C/hr.

CONCLUSION

In planning of UGT, geological condition should be considered as a most influential factor on design, erection and investment cost, and this condition is rather changeable depending on location. From the foregoing reason, some analysis on site is not always applicable to other site of construction. On the other hand, the external forces against the structure are rather complicated and not so clear; therefore, the past records have great importance for reference. Further theoretical and experimental analysis should be made to cope with unstable frozen soil problems and for reasonable planning. Arrangement of heat fence on the surface of side wall and/or bottom will give many advantages, since such arrangement permits formation of frozen soil which is limited in its extension.

Insulation effect should be based on insulation materials, when maximum boil-off gas ratio is limited precisely.

It is considered from public requirement in Japan that the service area of UGT will spread extensively for higher temperature substances such as LPG, in the future. In this case, cost will become one problem to be solved.

There is much difference in cost between an above-ground metallic tank for LNG and for LPG, but there will be small difference in UGT. This is due to civil work in UGT which occupies nearly a half or more than a half of total cost.

It will be our duty to develop more effective method which benefits possible cost-reduction as well as safety.

Availing ourselves of this opportunity, we express our thanks to Osaka Gas Co., Ltd., who gave us valuable advice in developing the UGT.