RESEARCH AND DEVELOPMENT OF DOWN-HOLE PUMPS IN THE SUNSHINE PROJECT IN JAPAN

MORI, Y., Tokyo Institute of Technology, Meguro, Tokyo 157, Japan

1.INTRODUCTION

This paper is a report of research and development activities with regard to down-hole pumps funded by the Sunshine Project of Agency of Industrial Science and Technology, Ministry of International Science and Technology of Japan. Among energies, even though at present the total electric power generation by use of geothermal energy is about 250MW, geothermal energy is considered one of the highly hopeful energy resources due to its large and promising reserves spread throughout Japan. Therefore in the geothermal energy R & D in the Sunshine Project, several essential, substantial and basic projects associated with advanced evaluation mothods, efficient and high temperature drilling technologies, effective geothermal energy utilizations, together with a means to enhance the percent of drilled production wells of the aimed production performance, have been carried out during the past decade. An important feature related to the geothermal resources in Japan is that over a half of the total resources contains hot and medium temperature brine of 140-200^{0}C. Therefore utilization of the hot brine should be seriously investigated. However, among newly drilled production wells, some are found to have brine of low pressure, not high enough to spout out by its own pressure. In order to pressurize the brine of low pressure enough to come up to the ground level, a down-hole pump, similar to a submerged pump driven by a motor, is concluded most promising after serious studies. By use of this kind of pump the thermal energy of hot brine sent up to the ground is taken out to be use in a binary cycle plant. From the viewpoint of utilization of hot brine and of environmental problems it is considered that an ideal geothermal plant is a binary cycle plant provided with a down-hole pump and generating no pollutive gases.

With the view and objective to make effective use of the hot brine of low spouting pressure, the R & D project for the submergible motor-driven down-hole pump was started in 1983. The project consisted of three major items, which were the development program of basic technologies, the test run of the No.1 machine for technical feasibility study which was to be designed and manufactured on the basis of the results obtained from the basic technologies developed and the test run of the newly developed No.2 pump mainly for economic feasibility study which would be designed in the light of the results of the run of the No.1 machine. By the end of 1988 fiscal year, most of the developments of basic technologies, and the manufacture of the No.1 machine and its long test run, using the real hot brine of 170^{0}C, were successfully completed. Based on the results thus obtained the No.2 pump with its operation system is now under construction for laboratory and practical well tests. The project will be finished by the end of 1988 fiscal year for check and review. Most of this paper describes the target and outline of the motor-driven down-hole pump R & D project and the results obtained so far.

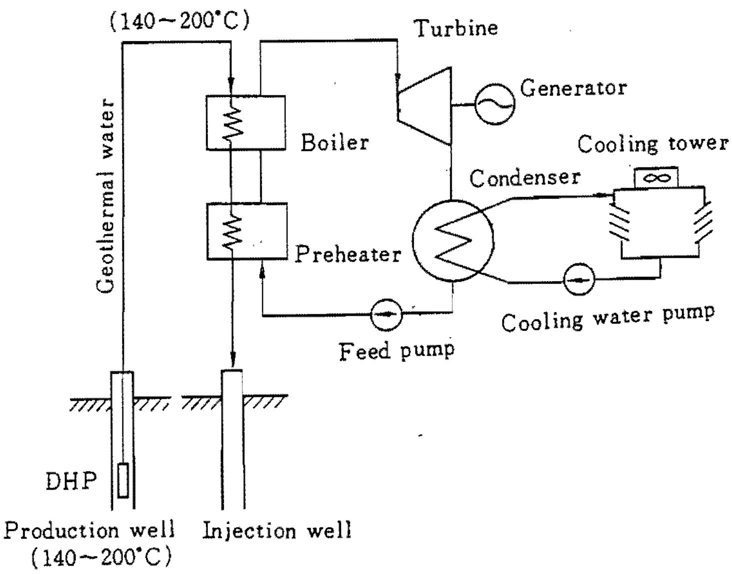

Figure 1, Binary cycle plant and D.H.P.

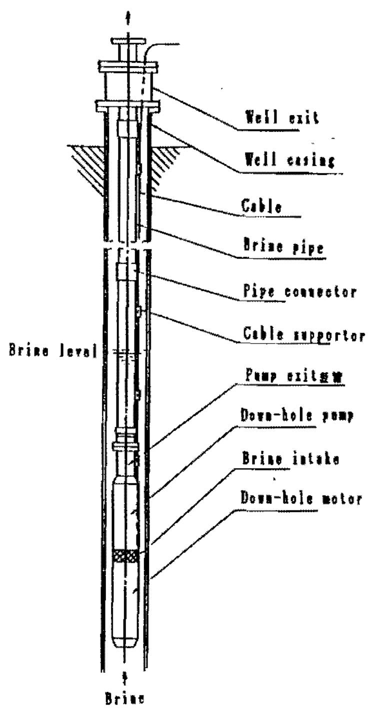

Figure 2, Motor-driven D.H.P.

2.BINARY CYCLE WITH DOWN-HOLE PUMP AND OUTLINE OF THE PROJECT

The project of the down-hole pump is administrated by the Sunshine Project Promotion Headquaters, AITS, MITI and implemented by New Energy Development Organization. It is steered by the Committee of Down-Hole Pump R & D of NEDO. The project is closely connected with the Project of the development of 10MW class binary cycle plant and the drilling Project of several wells for both the projects is also included. In order to achive the objectives of the projects, first of all, in the down-hole pump project prelminary studies were done to select the appropriate flow diagram connecting a binary cycle plant and a down-hole pump installed in the production wells and the type of the pump. For the binary cycle power plant as shown in Figure 1, the working substance of low boiling point should be properly selected in consideration of thermal efficiency, power cost, reliability and harmlessness superiority.

Until 1987, R-114 was selected as the material most suitable to the binary cycle using hot brine of about 200°C. As seen from Figure 1, the down-hole pump is installed at the position most appropriate to the binary cycle operation in proper consideration of not only pumping up the brine to the ground but also preventing the degasing of such gases as CO_2 or H_2S. However, since 1987 the global environmental problem of chlorocarbon gas has been seriously and internationally discussed, so the committee has been studying for an alternative and thermodynamically proper substance.

It is estimated by a preliminary cycle analysis on the assumption of exploitable geothermal supply in Japan that in the far future over a half of the electric power by geothermal energy will be generated in binary cycle plants of about 50MW output and that when the brine is over 200°C the binary cycle plant is superior to the flushing cycle plant. It is also calculated that for the binary cycle plant of 50MW class using the brine of 170°C the required flow rate of the brine is about 2800 t/h. When a production well produces 240t/h, about 12 production wells are to be provided for the plant and one down-hole pump must be installed in each of them. Thus, the down-hole pump is a very important and essential part to the binary cycle plant as it not only improves its thermal efficiency and reliability but also enhances the rate of operation of the plant. The success of the R & D is highly hoped for. In the processes of establishing the

	No.1 Machine	No.2 Machine	Practical Machine
ITEM			
Well Nominal Diameter(inch)	9·5/8	9.5/8	13·3/8
Well Practical Diameter(cm)	224	224	317
Brine Flow Rate (t/h)	50	100	300
Total Pumping Head (m)	300	340	400
Brine Temperature (°C)	140-170	170-200	140-200
Installed Depth (m)	400	400	500
Driving Power (kW)	100	200	500

Table 1, items and R & D target of D.H.P. Project

FY	1983	1984	1985	1986	1987	1988
Studies of Basic Technologies	Literature Survey·Fundamental Experiments· Check & Review					
1st Machine			Manufacture·Labora. & On-site Tests			
2nd Machine					Manufacture·Labora. & On-site Tests	

Figure 3, R & D schedule of D.H.P. Project target,objective and content of the down-hole pump project, it was assumed that the temperature of the brine was in the range of 140-200°C and the depth of pump installation in the well was about 300-600m. The following three items in the project were discussed as a matter of serious condiseration. The first item was to enhance the reliability of the performance and the rate of operation. The second was the compatibility of the pump to the narrow and curved well when operated under various conditions of the brine level change and flow rate fluctuation. The third was durability of the pump under severe physical and chemical conditions with such gases as CO_2 or H_2S, $CaCO_3$ or SiO_2, hard particles of sand and the wide range of pH of 4 to 8. In the process of selecting the appropriate type of down-hole pump, it was found that the line shaft-driven pump had a few R & D items and a high operating efficiency, but was not used in a curved well and would have some trouble because of many bearings for the driving shaft and deep well. The turbine driven pump may be fit to a particular binary cycle plant which has not been studied in detail. In consideration of the facts mentioned above and the recent advancement of insulators of motor wires and power cables operated in the hot brine, the down-hole type of motor driven pump was selected as the appropriate one for the binary cycle plant in Japan.

The specifications thus decided on as the R & D targets of No.1 and No.2 test machines in the project and those contemplated for the practical pump are shown in Table 1. As explained already, in advance of the design and manufacture of the No.1 machine, the fundamental and basic research studies and the test run of the No.1 machine were successfully finished. The No.2 machine has been already made and a laboratory test is going to be made.

The schematic picture of the typical down-hole pump developed in the project is shown in Figure 2. The pump is installed down in a well when the level of the brine is a little above the pump. The driving motor composes the lowest part of the machine and the centrifugal multistage pumps compose the upper part. These main parts of the machine are each supported by the two radial plane bearings and the one thrust bearing, and connected together. The hot brine is taken in from between the motor and pump and is pressurized going through the pump stages. the pressurized brine is sent upward through a brine tube and the power cables and the wires for monitoring sensors are fixed around the brine tube. In order to make successful progress in developing a down-hole pump satisfying the specifications explained above, a careful, detailed and practical R & D schedule was formulated including fundamental studies of essential components and monitoring ways. The R & D schedule thus made is shown in Figure 3. The project started in 1983 and will end in the fiscal year of 1988 with the completion of the field test of No.2 machine and the check and review of the total results. A steering comittee composed of experts from AIST and NEDO, universities and private sectors makes practical R & D plans and discusses the results obtained to make efficient and rapid progress. Researchers and engineers of six compainies take part in the project. Ebara Co. is the main contractor for the down-hole pump itself as a hard ware, and at the same time is in charge of operation run. Mitsubishi Electric Co. takes care of the motor part, Sumitomo Electric Inc. is responsible for the power cable and Idemitsu Kosan Co. for lubrication and insulation oils. Electric Power Development Co. and Geothermal Energy Resources Development Co. take charge of the evaluation of production well potential and effectiveness of down-hole pumps in various underground conditions.

3. R & D OF BASIC NEW TECHNOLOGIES OF D.H.P.

Fundamental researches have been performed on about 12 items including one for consolidating the technologies developed and the monitoring system. The main research items are materials, brine bearing, shaft sealing mechanism, thrust plain bearing of ceramics at high temperatures, stator coil wires, lubrication and insulation oils, power cables at high temperature and pressure, the connecting method of power cable, the fixing and supporting method of cable and the mothod of consolidating the results obtained in No.1 machine.

3.1 Materials.

The material of the pump impeller has to be provided with anti-corrosive and erosive property to high speed brine. Several promising materials were selected and tested to pick up the most reliable material. The material was used to make the impeller of the pump and the outer casings of the pump and the motor.

3.2 Brine bearing.

Due to the dimension limit caused by the small inner diameter of the well, the outer diameter of the pump impeller is not large and many stages are required to bring about the needed pressure ratio. Consequently, several plain bearings are to be used between stages, but they are not able to be lubricated by oil because of the constructional restriction. Therefore brine itself has to be used as lubricant. By the selection of appropriate material for the bearing, the development of brine bearing with satisfactory durability for the brine containg sand and of small friction coefficient was sucessfully achieved.

3.3 Sealing mechanism.

In the down-hole pump, the thrust bearing of the brine pump and bearings of the motor are fed with lubricant specially developed for high temperature use. However, in order to prevent contamination by brine and deterioration of lubricative performance of oil, the sealing mechanism newly developed for this purpose was found to have superior durability and reliability even in the corrosive brine containing sand.

3.4 Thrust bearing.

The thrust bearing, which supports the total weight of the down-hole pump, is lubricated by lubricant oil for high temperature use. The viscosity of lubricant decreases remarkably with temperature, and the ceramic compact thrust bearing which can carry high loading under low viscosity lubricant oil for high temperature use. The viscosity of lubricant decreases remarkably with temperature, and the ceramic compact thrust bearing which can carry high loading under low viscosity condition was developed. Thrust bearings and shaft seals were tested for 1.000 hours in hot water of 200°C and of 20kg/cm^2 pressure. Lubricant of high grade refined mineral oil was used. Although a very small amount of water was found in the oil after the tests, no deterioration of lubricative performance was observed from the viewpoint of practical use.

3.5 Stator and rotor of the motor.

The motor stator is electrically heated up above the temperature of the brine by the current sent in the wires of stator. Therefore, the most important problem is the heat resistive property of the electrical insulator for coil wires such as of polyimide film. Evaluation tests for thermal resistance and life of polyimide at 300-400°C for 5,000 hours were done. Mechanical strength of film was also tested under high temperature conditions and no decrease of strength was found out. Creep tests were also performed for polyimide enamel/ polyimide tape wound wires, which were found to have no serious deterioration.

Concerning the electric properties of electrical insulators, tests of breakdown voltage of coil were made by use of reliable insulators such as polyimide and a tendency of slight increase of breakdown voltage was observed. Cooling problems of the motor should be discussed on the stator and rotor. As seen in Figure 2, the brine flowing outside the outer casing of the motor is the ultimate cooling material. The stator is directly cooled by forced convection of brine. The close relation between the insulation oil maximum temperature and the flow rate is given because of the strict limitations of allowable maximum oil temperature and the oil flow rate due to the limited maximum oil passage size. The optimum flow rate of oil should be selected. Figure 4 is an analytical results based on several experiments.

As important mechanical engineering problems about the stator and rotor, two research items were specially taken up and studied. One is the vibration problems of the rotor and multi-stage pump which are so connected as to rotate as one body. Particularly, a vibration analysis of the motor under operating condition and faulty or starting or stopping condition was made in the process of designing the rotor. The vibration performance was investigated in detail in a laboratory test in hot water by use of many vibration sensors for several conditions. No serious problem was found even in the field test of No.1 machine. The second mechanical problem associated with the motor is that related to the thermal expansion and thermal stress due to the high temperature of brine. The thermal expansion problem between the stator and rotor was solved with a design that provided a mechanism to take care of the expansion difference between the stator and rotor. Fatigue strength of over 50 kg/cm^2 of the selected metal was observed at the repeat number of 10^5 , which is of quite high valve in comparison with the value of 21kg/cm^2 obtained in the stress analysis.

3.6 Construction of the No.1 and No.2 motors.

The construction of the No.1 machine is of a combination of a motor and a multi-stage water pumps of centrifugal type. As seen from Table 1, the input of the motor is 100kW and the motor constructs the lower part of the slender down-hole pump. The No.2 machine is planned to be used for a production well of larger flow rate such as 100t/h, twice the rate of No.1 machine. Therefore as regards the No.2 machine it was found by a preliminary study of its construction that the motor of No.2 machine has to be of a tandem construction in consideration of its limited outer diameter and required large driving force. Two separate motors of No.2 machine have the same mechanical construction, that is, each motor has two radial bearings and has almost the same dimension. The connection of the two motors was made by use of a spline type construction.

3.7 Lubrication and insulation oils.

The temperature of the stator and rotor of the motor is estimated to be considerably higher than the temperature of the brine, due to self-heating by electric current. And it is

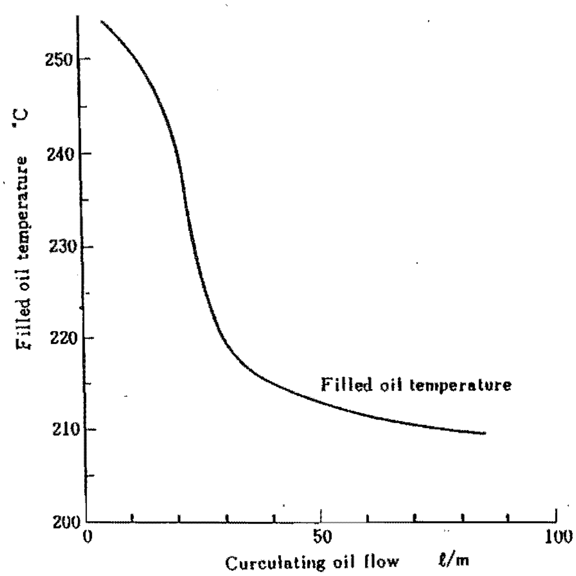

Figure 4, Cooling performance

considered not to be easy to develop lubrication and insulation oils which can be used with high reliability and durability over $300^{\circ}C$ for a given period. Considering this condition, the system to cool the oils was developed and the reliability of the oils was confirmed by experiments. Lubrication oil was circulated by a specially designed small centrifugal pump without a diffuser and cooled when it flowed in the narrow rectangular channels of axial direction welded around the motor outer casing. Insulation oil was cooled by free convection at the remaining part of the outer casing between the cooling channels of lubrication oil.
In advance of the tests with the No.1 machine, complex thermal stability tests were performanced to select promising candidates for high temperature bearing and insulation oils. It was found that slight seepage of water accelerated the decomposition of both high grade refined mineral oil and silicone oil used as lubrication oil, and that the former was relatively stable than the latter. The evaluation of canditates for studying insulation oil also confirmed that high grade refined mineral oil was preferable in terms of its electrical performance and stability.

3.8 Cable and cable connections.

As the down-hole pump is installed at the depth of 300-600m down in the production well, a long power cable which is required to be provided with high thermal stability and durability in corrosive and erosive brine and to be bended as to be wound around the brine tube in a snaky manner. In addition to these conditions, even a small pinhole in the covering layers of the cable may result in the stoppage of the plant operation. In other words, the cable gas has to be of mulitlayer construction for electrical insulation, pressure durability and anti-corrosion, and the cable connection part should be of a construction that can slove the problem of a large thermal expansion difference between the metal sheath composing the pressure boundary and the teflon as an insulator. The cable connecting parts have to be carefully studied. The other important problem is the method of connecting the cable to the motor, because the method is taken into account the thermal and corrosion problems and the on-site fabriation. Several types of cable cansisting of insulator, metal sheath and anti-corrosion layers are made. For the No.1 machine, the diameter of the central conduct is 5mm, the thickness of inner insulator is 1mm and metallic sheath is 0.4mm. The anti-corrosion layer is 1.5mm and the cable outer diameter is about 15mm including the repressing tape layer. The temperature of the brine for the No.2 machine is $200^{\circ}C$, only $30^{\circ}C$ higher than No.1. It was decided, however, that the construction and materials for the No.2 machine, which was to be operated under severe condition, should be different from those adopted for the No.1 machine. For the No.2 machine, as main metallic

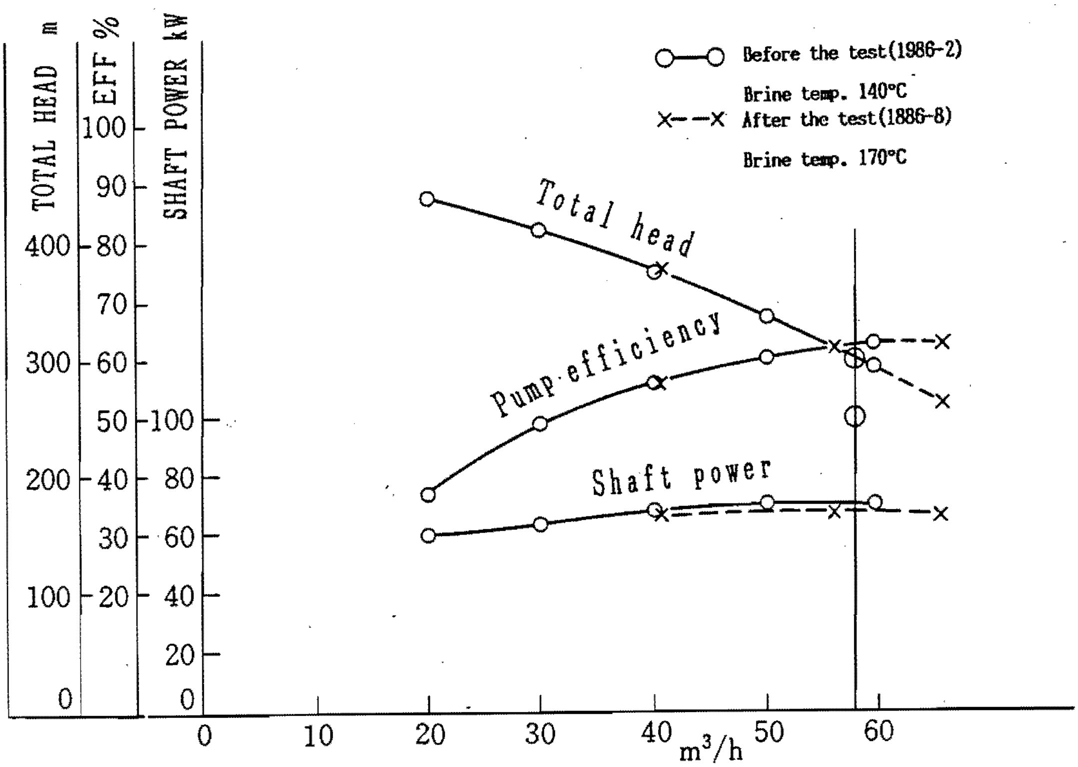

Figure 5, Pump performance before and after the duration test of No.1 machine material for cable sheath, cable connection part and the part of the cable and motor, Incolloy 825 and Inconel 625 were tested. In order to solve the thermal expansion problem, the metal sheath was welded to the metallic bellow of the cable connection part which forms the pressure boundary. For the inner insulation layer and outer anti-corrosive layer, different materials from those used for No.1 machine were newly developed.

4. DESIGN AND RESULTS OF TEST RUN OF NO.1 MACHINE.

4.1 Design of No.1 machine.

The main specification of the No.1 machine is as shown in Table 1. Additional specifications are as follows; the revolutional speed is 2850 rpm, the power is 70.5 kW, the stage number of impeller is 24, the motor is of 2 poles and is driven by 3 phase-50 Hz current. The total length is 9m and the outer diameter is 210mm at the pump section. The pump is of vertical axis and mixed-flow impeller with a multi-wing diffuser and is provided with mechanical seals. The motor is of cage-type three phase induction. The stator is of coaxial winding. The rotor is of closed slot squirrel cage type. The motor is of oil-seal canned submergible type. The overall length of the motor is 3650mm. The passage of the insulation oil consists of 18 paths of 20mm width and 5mm height. Analyses of the rotor were made for the characteristic frequency and vibration performances and it was ascertained that the primary resonance frequency was larger than the operating frequency. Likewise, it was confirmed in consideration of the rigidity of the shaft and the motor can and the spring constant of all the bearings that neither the maximum amplitude nor acceleration due to vibration pose any problems for operation performance at all.

4.2 Test runs at the laboratory.

The test runs at the laboratory were performed from January through August, 1986, 500 hours run at 140°C, and the suceeding 2000 hours run at 170°C. The laboratory test loop consisted of a pump barrel, a water heater and a circulation pump. The No.1 machine was able to be tested under controlled high temperature and pressure conditions. Temperature sensors were set on the pump and various parts of the hot water circulating rig and the pressure at several points of the loop and flow rate of water were measured. The laboratory run at 170°C was carried out for four months, with several short stops in that period of time. In Figure 5, the pump performance before and after the run is shown. There is no difference between the two performances. The vibration performance of the No.1 machine was measured and analysed. Even though the machine is a long unit consisting of pump and motor and of elastically supported construction, its vibration amplitude was found to be small and the very stable operation was confirmed in the hot and high pressure water. Based on the results obtained in the laboratory test run and in the over-haul after it, it was showed that there were no damaged or worn-down parts and components.

4.3 Evaluation of the production well for the field test of the No.1 machine.

In parallel to the projects of the basic R & D, the design and test run of the No.1

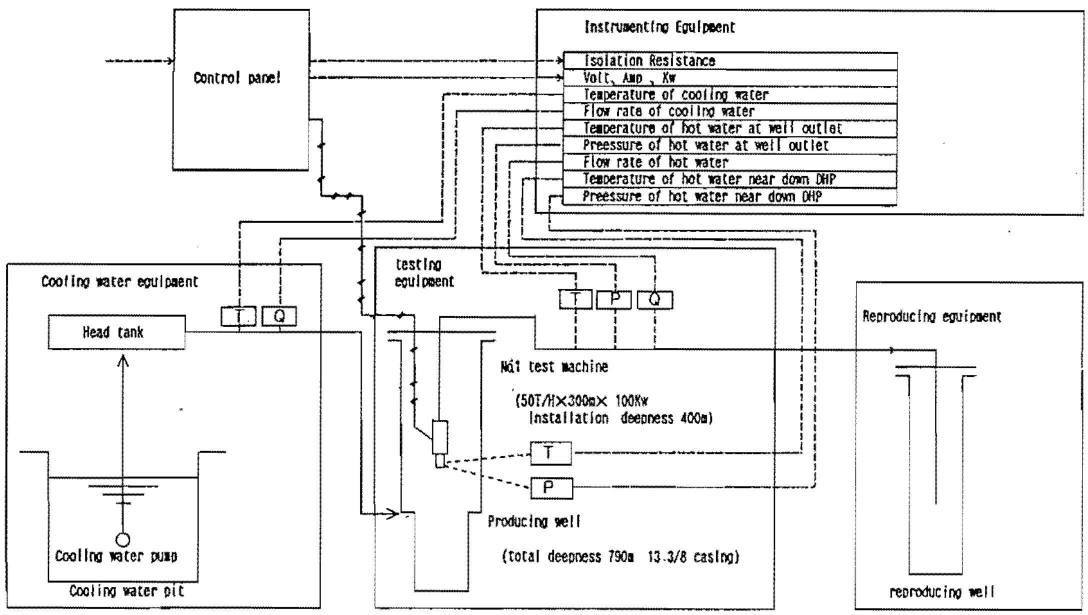

Figure 6, Measurement and control system for field test machine, the evaluation study of the bored production well for the field test run of the No.1 machine was made. First of all, based on the test results of a bored well, a computor program for evaluating the performance of the bored well and the production well capacity indicated by such parameter as the production index during the pump operation was developed to predict the performance of the brine in the well by use of the down-hole pump. The condition for degasing the CO_2 in the well on the way up to the ground was discussed in consideration of the relation of degasing and decomposition of scale along the well wall. Based on these many essential studies, the No.1 machine was installed in the bored well in the Sugawara District, Kokonoe-Machi, Ohita Prefecture, Kyushu area. By use of the results obtained from the bored well without the down-hole pump, the well performance enhanced by the No.1 machine was predicted. The prediction was confirmed to be accurate with regard to the brine performance when a down-hole pump was adopted for the brine whose pressure was not high enough to send it up to the ground level. As the result, the bored well available for the test of the No.1 was found to be used for the field test run of the No.1 machine.

4.4 Test run procedure of No.1 machine.

The flow diagram and the measurement and instrumentation system are shown in Figure 6. The temperature of the brine itself at the position of the down-hole pump inlet is about 200°C, but as the specified temperature for the No.1 is 170°C the brine inlet temperature to the pump was lowered to 170°C by mixing water of room temperature sent from a river on the ground level. Gases contained in the pumped-up brine was separated from the brine at the separator on the ground and the brine was sent back down to the recirculation well. The test machine was installed at the depth of 400m down in the well. The pressure of the brine at the down-hole pump position was about $23kg/cm^2a$. The average flow rate of the brine was $60m^3/h$. During the long-term operation of about 1,000 hours from January 1987 through the middle of March, special attention was paid to the electrical insulation between the cables and brine and to the inlet temperature of the brine. After the 1,000 hours run was completed, the pump was immediately recovered, transported to the laboratory shop and disassembled for inspection and evaluation of every part of the tested machine. The results of evaluation of the tested pump showed that there was nothing wrong with respect to the bearings including the ceramic and insulative brine bearings, shaft seals, motor insulation, cable and cable connector, and lubricative oils. The analysis of experimental results obtained about the pump and motor performances proved good agreement between the predicted and experimental performances.

5. FUTURE TASKS.

The main differences in specifiction of the No.2 pump from the No.1 are, as shown in Table 1, the inlet temperature of the brine and the flow rate. These two factors introduce very important problems to be solved. For the large flow rate problem, the motor of 100kW input has to be of a tandem construction and the temperature which is 30°C high than for the No.1 pump, needed studies not only of construction materials such as insulator and metals and oils, but a new construction that can prevent serious damage by corrosion and thermal expansion.

The continuous operation of 2,000 hours in the laboratory and 5,000 hours in the field test are planned. This long operation time requires the introduction of a monitor system suitable to the long time field run of the No.2 pump. A reliable system for this purpose has to have the capability to pick up even the slightest abnormal performance of the pump in the run, and should consist of sensors of temperature, pressure and pump vibration and a data processing computor. The monitor system is essential not only for the development of a future system that will make a computor controlled operation possible, but also for the enhancement of reliability of the motor driven down-hole pump to practical use.

6. CONCLUDING REMARK.

The research and development of the motor-driven down-hole pump, the project of which was started in 1983, has been carried out almost on schedule. Based on the results of the study of basic components, the No.1 down-hole pump for the brine of 170°C was designed and manufactured and its test run was conducted in early 1987. The target of the No.1 machine was attained by a continuous 1,000 hours operation, which was considered the world first success of the motor-driven down-hole pump for 170°C brine.

Following the No.1 project, R & D of the No.2 down-hole pump for the brine of 200°C and for 7,000 hours operation was launched with several new important studies on insulators, oils, bearings, metals and construction. The main target of the No.2 machine is pursuit of the temperature limit for the motor-driven down-hole pump, the economical feasibility and reliability in long continuous operation. The success of the development of a down-hole pump is considered not only to make contributions to more effective utilization of geothermal energy in Japan which is predicted to have a large hot brine supply, but also to render technical help to foreign countries in developing geothermal energy. The combination of the binary cycle plant and the down-hole pump pressuring the brine in the production well is expected to constitute an ideal geothermal energy system in the future which takes out the thermal energy of the brine to the binary cycle plant without generating any pollutive gases such as H_2S or CO_2 or causing the deposition of scale in the well.

Lastly, the author would be honored to stress that the Project of the motor-driven downhole pump is fully supported by the Sunshine Project of Agency of Industrial Science and Technology, Ministry of International Trade and Industry of Japan and also to express his hearty appreciation as the Chairman of the Project for the efforts and cooperation of the members of the Steering Committee of the Project and to the researchers and engineers of six companies under contract to the Project, which are Ebara Co., Mitsubishi Electric Co., Sumitomo Electric Ind., Idemitsu Kosan Co., Electric Resources Development Co., and Geothermal Energy Resources Organization Co.