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GEOTHERMAL POWER PLANT

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I. FOREWORD

Fuji Electric delivered the first geothermal power plant to Fujita Kanko Co., Ltd. Hakone Kowakien in 1960, well before the first oil crisis. Since the oil crisis, geothermal energy has been explored as a new source of energy to replace oil and the construction of geothermal power plant is promoted around the world. Fuji Electric has received orders of several types of geothermal power plants from El Salvador, USA, Philippines and Iceland, some of them have already been delivered and others are currently in design and manufacturing stages. These plants will be introduced at another chance. This article describes the features of our steam turbine for geothermal power plants and our research and development on geothermal power generation as an introduction to our geothermal power generation technology.

II. FEATURES OF FUJI GEOTHERMAL STEAM TURBINE

Our steam turbine used in geothermal power plants has several special features. Of these, the main features are:

1. Turbine casing

The geothermal steam turbine can have the same construction as that of low pressure casing of steam turbine for conventional thermal power plants.

Fig. 1 shows the cross section of double flow geothermal steam turbine. As can be seen from this figure, the so-called separate bearing pedestal is adopted, in which the front and rear bearing pedestrals are separated from the turbine casing and are independently mounted on the turbine foundation.

2. Turbine rotor

A drum type rotor forged from a single ingot, the same as that of our conventional steam turbines, is used.

3. Turbine blading

Except for the last standard low pressure blades, 50% reaction blading, the same as that of conventional steam turbines, is adopted.

Since the geothermal turbine operates in steam containing solid impurities and corrosive gases, the following points must be taken into consideration in blade design:

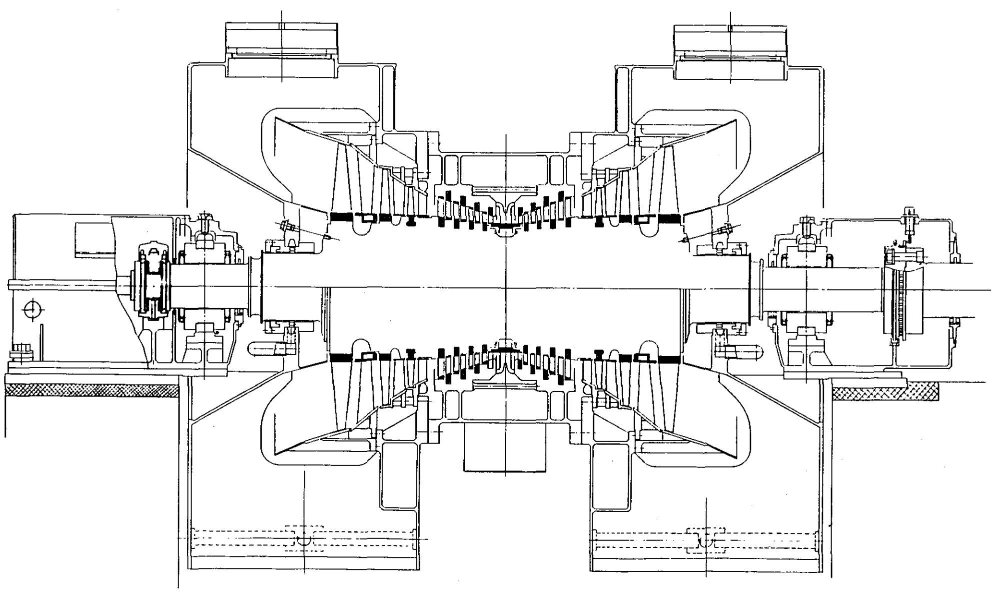


Fig. 1 Cross section of double flow geothermal steam turbine

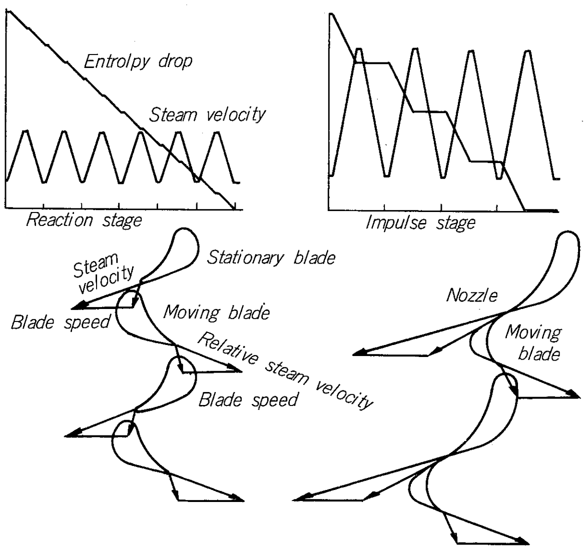
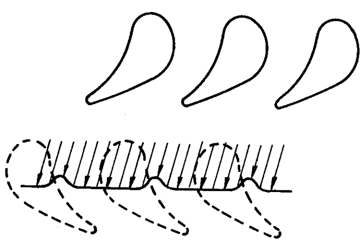
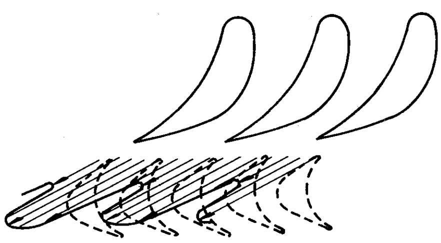


Fig. 2 Steam velocities of reaction stage and impulse stage



(a) Reaction stage



(b) Impulse stage

Fig. 3 Nozzle passing excitation of reaction stage and impulse stage

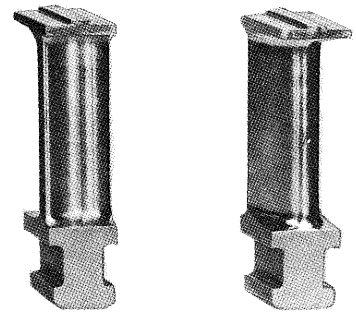


Fig. 4 Moving blade with integral shroud

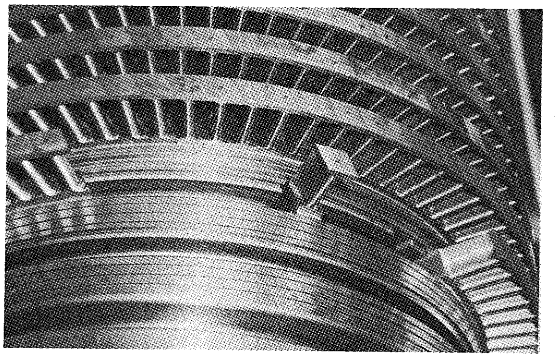


Fig. 5 Blading work

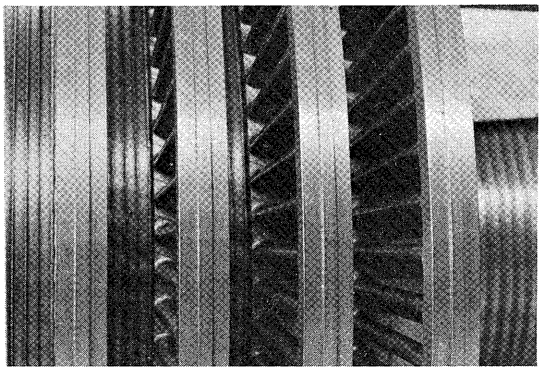


Fig. 6 Integral shroud after finish machining

(1) Corrosion and corrosion fatigue of blade material
(2) Erosion on blade surface due to water droplets and solid particles in the geothermal steam.
(3) Deposition of impurities in the geothermal steam on blade surface.

As shown below, the reaction blades are extremely reliable against these severe conditions to which a geothermal turbine is exposed.

1) Low steam velocity

Under the optimized design conditions in thermodynamics, number of stages of reaction turbine is approximately 50% more compared with that of impulse turbine. Therefore, in case of reaction turbine, the heat drop at each stage is smaller accordingly. Furthermore, in case of reaction turbine, the heat drop at each stage is converted into velocity equally shared by the stationary blade row and moving blade row. Therefore, the steam velocity at the reaction stage is approximately one-half of that of impulse blades. *Fig. 2* shows the comparison of the steam velocities of the reaction stage and impulse stage.

Since the erosion by water droplets and solids particles in the steam is proportional to the 3rd power of the steam velocity, reaction stage used under low steam velocity has far superior erosion resistance and longer life compared with impulse stage and is suitable to a geothermal steam turbine.

2) Low nozzle passing excitation

To prevent a drop in turbine efficiency, the axial gap between the nozzle and moving blades at impulse blades must be kept as small as possible. However, the axial gap of the reaction blades can be made larger without the deterioration in efficiency. Therefore, the nozzle passing excitation is much smaller than that of impulse blades and the cyclic stress imposed on the moving blades is essentially small. *Fig. 3* shows the nozzle passing excitation of the reaction stage and impulse stage. This is also one of the advantages for a geothermal steam turbine that operates in corrosive geothermal steam and is exposed to corrosion fatigue.

3) Adoption of an integral shroud ring

When a shroud ring is riveted to the moving blades, a large residual stress remains on the riveted tenon and stress concentration cannot be avoided. Therefore, riveted shroud ring is not recommendable to the geothermal steam turbine which operates in a corrosive atmosphere.

Our geothermal turbine uses the integral shroud ring, which is widely used in our conventional steam turbines and has ensured completely successful experience without any blade failure. As shown in *Fig. 4*, *5*, and *6*, the shroud is machined from a piece of material integral with the moving blade. As can be seen in *Figs. 5* and *6*, the shroud of adjacent blades contact each other and the friction between the contacting shrouds effectively dampens the vibration of the moving blades.

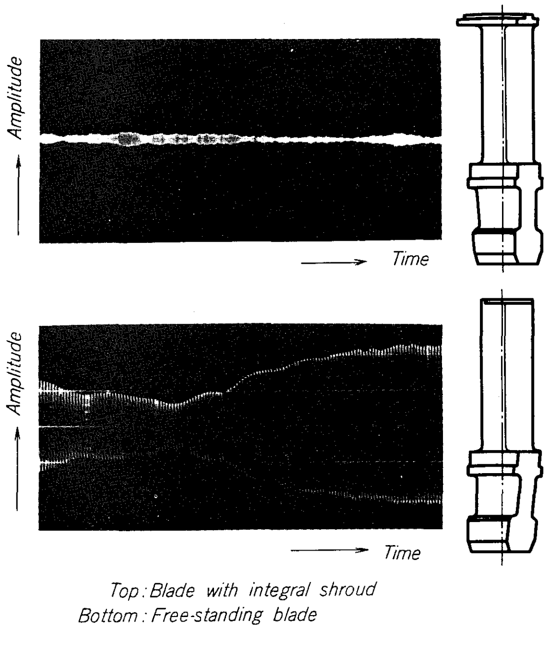
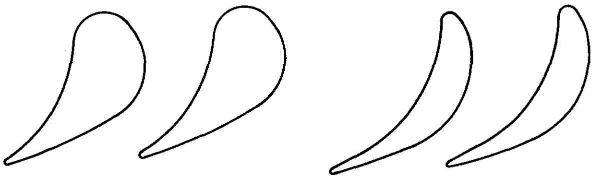


Fig. 7 Vibration damping effect of integral shroud

Fig. 7 is a comparison of vibration damping effect of a moving blade with integral shroud and a moving blade without integral shroud. The superior damping effect of the former minimizes the blade vibration amplitude. Therefore, a moving blade with integral shroud ring can be said to be perfect for a geothermal steam turbine which is exposed to corrosion fatigue.



(a) Modern design (round head) (b) Old design (thin profile)

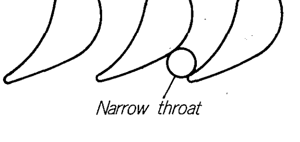
Fig. 8 Reaction blade profiles

4) Adoption of round head type reaction blade profile

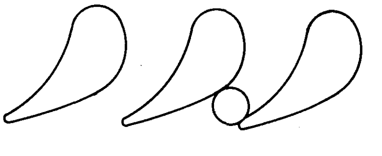
The round head type reaction blade profile developed for large capacity, high temperature and high pressure steam turbines for thermal power plants is also used with the geothermal steam turbine. *Fig. 8* is a comparison of this newly developed blade profile and the old blade profile. As can be seen from this figure, the new round head type blade profile has a thick and round leading edge. Therefore, the stress caused by the steam force is much lower than that of the old thin profile. Moreover, it is also a safe design having a sufficiently high natural frequency. The affect of blade erosion, etc. on the profile performances of the round head type reaction blade is less than that of the old thin blade profile. This also makes it suitable for a geothermal turbine.

5) Adoption of a blade profile having larger chord length

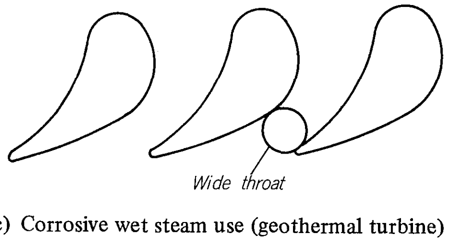
Corrosive atmospheres, such as geothermal steam, reduce the fatigue strength of blade material noticeably, therefore the corrosion fatigue strength of the material must be taken into consideration in the design of the blades of a geothermal turbine.



(a) Superheated steam use (conventional turbine)



(b) Corrosive transition zone use (conventional turbine)



(c) Corrosive wet steam use (geothermal turbine)

Fig. 9 Blade profiles for various steam properties

Our geothermal turbine uses a blade profile having a large blade chord. This suppresses the bending stress of the blade to less than that of the conventional steam turbine and provides a high blade natural frequency. On the other hand, the possibility of steam path choke due to deposition of impurities in steam is reduced extremely by the provision of wide throat at blade outlet.

Fig. 9 is a comparison of the blade profile of a conventional steam turbine and a geothermal steam turbine. These blade profiles are shown in the same scale to facilitate comparison.

4. Low pressure long blade

Because the steam volume increases rapidly at the low pressure part of a turbine, long blades are necessary. However, a number of big problems such as high stress produced by the large centrifugal force, resonance due to the low natural frequency, erosion of the blade surface due to operation in wet steam etc. that require careful attention are involved in using such pressure long blades. These problems have been solved and the safe operation is guaranteed with the blades used in our geothermal steam turbine by adopting the following blade construction.

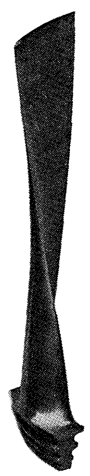


Fig. 10 Low pressure long blade

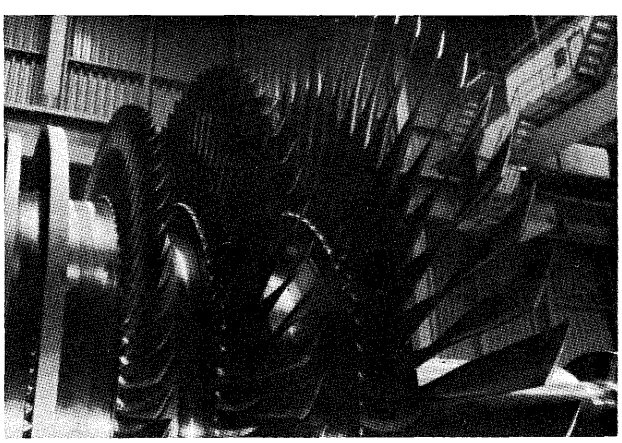


Fig. 11 Rotor with self-standing LP blades

1) Self-standing LP blade

Fig. 10 is an exterior view of the low pressure long blade and *Fig. 11* shows the rotor with self-standing LP blades. As can be seen from these figures, shroud rings, lacing wires, etc. are not used in our low pressure long blades and the low pressure blades stand independently. This construction is also used in our conventional steam turbines. This is the reason why it is called a self-standing blade and is the biggest feature of our low pressure long blade. Self-standing LP blade is provided with following excellent features.

(1) Safe design without shroud rings or lacing wires

So far, in low pressure blade, almost all troubles have occured relating to riveted shroud ring and lacing wire. FUJI's low pressure blade made of single piece material is self-standing and free from those troublesome constructions, therefore it is very safe and is most suitable for geothermal steam turbine operated under corrosive and erosive conditions.

(2) Nonresonant design through accurate tuning

Since the steam flow around the blade row is not uniform, low frequency excitation force works on the blade. Since the natural frequency of the low pressure long blade is low, it may resonate with this excitation force. However, the resonance of the blade due to excitation force composed of harmonics, which are integral times of turbine speed, can be easily suppressed by means of accurate tuning of blade natural frequency. In order to ensure the accurate tuning of natural frequency, the mode of blade vibration must be as simple as possible. This is one of the reason why FUJI's standard LP long blade is designed as a self-standing blade without any shroud or lacing wire. *Fig. 12* shows an example of Campbell diagram representing the relationship between the natural frequency and rotating speed of low pressure blade.

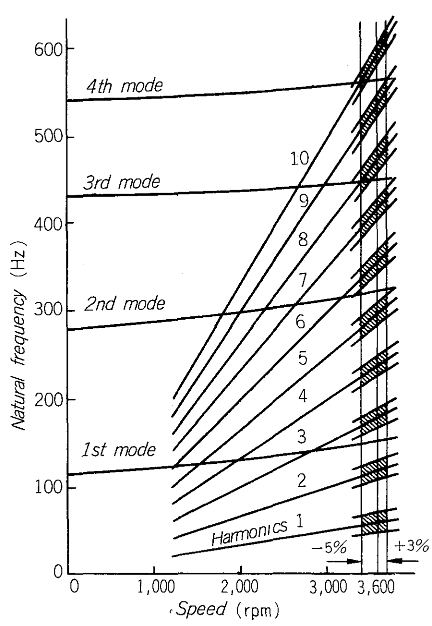
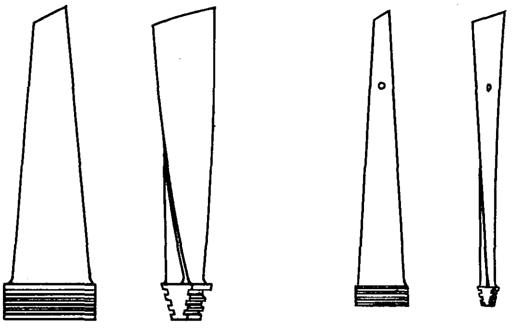


Fig. 12 Campbell diagram



(a) Self-standing low pressure blade (b) Old low pressure blade

Fig. 13 Modern and old LP long blades

(3) Low stress level

Our self-standing low pressure blade uses a blade profile that is thicker and has a larger chord length than the old design low pressure blade with lacing wire as shown in *Fig. 13*. Since the profile section of this blade is large, the stress level is low and it has sufficiently safe strength even when a decrease in the fatigue strength of the blade material caused by the geothermal steam is taken into consideration.

2) Protection against erosion

Since the inlet steam of most geothermal steam turbines is in the saturated condition, the wetness at the low pressure part is large and protecting the low pressure blade against erosion due to water droplets in the steam is extremely important. The following measures are taken at our geothermal steam turbine to protect the blades against erosion.

(1) Stellite shield

Erosion of the blades is prevented by plating a hard stellite shield to the leading edge of the low pressure blade onto which the water droplets in the steam collide. This method is also widely used at the low pressure part of conventional steam turbines.

(2) Large axial clearance between stationary blades and moving blades

Since the axial clearance between the stationary blades and moving blades of our turbine is large, the water droplets flowing from the trailing edge of the stationary blades are sufficiently accelerated by the steam flow until they reach the moving blades where they are broken up into little particles. Since the difference of velocity of the water droplets and the steam is, therefore, small and the water droplets give very little shock to the moving blades, hence the erosion action is reduced.

III. RESEARCH AND DEVELOPMENT ON GEOTHERMAL POWER GENERATING EQUIPMENT

A geothermal power plant involves various problems such as corrosion of material by the hydrogen sulfide, chlorine ions etc. in the geothermal fluid, erosion of the equipment by the water droplets and impurities in the steam, and exhausting of the large amount of non-condensable gases in the geothermal steam not encountered in conventional steam power plants. To solve these problems and supply reliable geothermal power plants, we are conducting research and development on the following items and the results are reflected in the design and manufacturing of the geothermal power plants.

1) Materials corrosion tests
(1) On-site corrosion test
(2) Stress corrosion cracking test on blade material
(3) Corrosion test on blade material
2) Condenser model test
3) Moisture separator model test
4) Field exposure test on electrical and instrumentation equipment

The following outlines the materials corrosion test and condenser model test.

Table 1 Corrosion test of materials performed by Fuji Electric

Test site	Test period	Test environment					
		Low velocity steam	High velocity steam	Con-densate	Aerated con-densate	Moisture separator drain	Circu-lating water
Fuji Electric Test Laboratory	August 1977 ~ present	Simulated environ-ment					
Electric Power Development Corp. Onikobe Geothermal Power Plant	November 1977 ~ July 1979	X		X			
Olkaria, Kenya	October 1977 ~ October 1978	X					
Ahuachapan, El Salvador	May 1978 ~ present	X	X	X	X	X	X
Palimpinon, Phillippines	January 1980 ~ June 1980	X			X		
Geyesers area of California, U.S.A.	June 1980 ~ November 1980	X			X		
Keflavik, Iceland	June 1980 ~ November 1980	X			X		

1. Materials corrosion test

As previously mentioned, various unique problems are involved in a geothermal power plant. Of these problems, the most important one is the corrosion of materials. We have performed various materials corrosion tests and select the suitable matierals and decide their usage conditions based on the results of these tests.

1) On-site corrosion test

Construction of geothermal power plants in various parts of the world was accompanied by numerous materials tests in both the laboratory and at the site and the standard for the material selection and usage conditions have been tentatively established basing on the results of these tests. However, since the properties of the geothermal fluid differ with the geothermal well, materials corrosion should be checked at each plant. On-site corrosion tests using the actual geothermal fluid are performed at the geothermal power plant construction sites responding to this requirement.

As shown in *Table 1,* Fuji Electric has conducted corrosion tests in many areas of the world. The following introduces the test performed at the Ahuachapan power station in El Salvador, Central America as an typical example. *Fig. 14* shows the test device installed at the site and *Fig. 15* shows its schematic diagram. The device consists of six test chambers to provide six different test

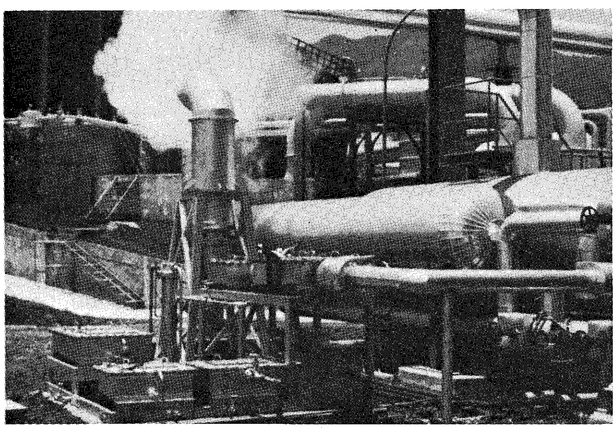


Fig. 14 Corrosion test device installed at Ahuachapan geothermal P/S, El Salvador

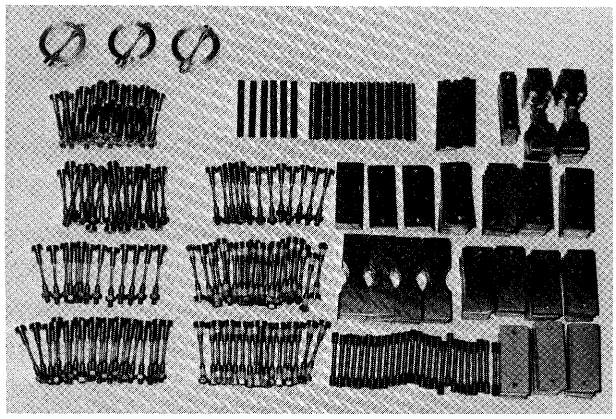


Fig. 16 Test pieces before exposure

environments. Fifteen kinds of major materials used in the plant were tested in these chambers. *Fig. 16* shows the test pieces.

(1) Test environments

1 Low velocity steam

This mainly simulates the environment in the turbine. The various characteristics related to corrosion of the materials of each part of the turbine by geothermal steam are tested.

2 High velocity steam

This is the environment for testing the erosion of the turbine blades and other parts exposed to high velocity steam with the water droplets and solid impurities in the steam. The low temperature steam from the low velocity steam test chamber is accelerated by throttling through nozzles and sent to this chamber.

3 Condensate

This environment corresponds to the condensate system and the wet steam region of the turbine. The exhaust from the high velocity steam test chamber is led to a condenser and the condensate obtained at this condenser is used.

4 Aerated condensate

The aerated geothermal steam condensate has an especially noticeable corrosion action due to the polarization action of oxygen dissolved in the condensate. This en-

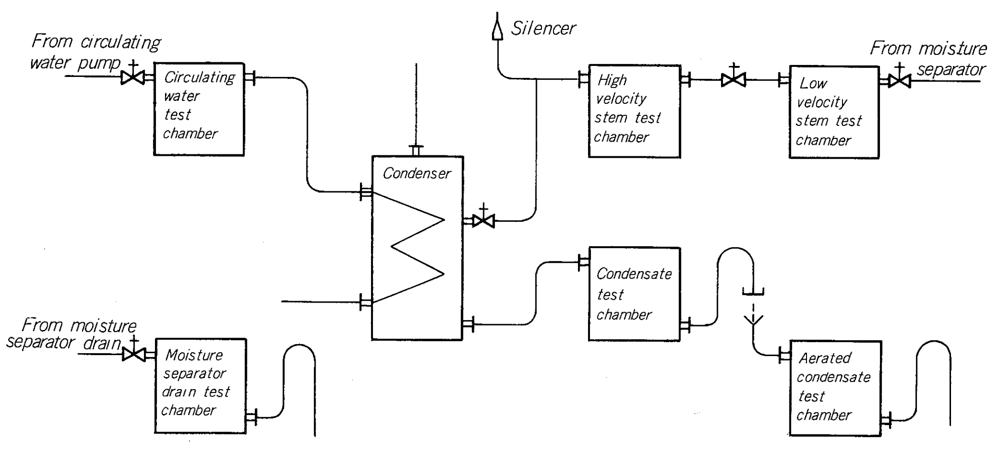


Fig. 15 Schematic diagram of corrosion test device

vironment is used to test this action. This corresponds to sealing glands of turbine at which a small amount of steam leakage occurs and to a condensate system that has an opportunity to contact with the air.

5 Moisture separator drain

This environment simulates the case when the moisture in the geothermal steam is not completely separated and flows into the downflow equipment.

6 Circulating water

The cooling tower water is circulated and used as the condenser cooling water in the geothermal power plant and the turbine condensate is used as make-up water to replenish the portion lost by evaporation at the cooling tower and other causes. Therefore, the circulating water has properties resembling those of the circulated and concentrated geothermal steam condensate and is fairly corrosive. This environment is used to test the materials used in the circulating water system equipment and piping.

(2) Kinds of tests

1 Corrosion test

This test is performed to examine the general corrosion conditions. The material is evaluated by measuring the thickness reduction and weight change caused by corrosion and microscopic examination of the overall corrosion, pitting, and intergranular corrosion conditions.

2 Stress corrosion cracking test

This test checks the strength of material which is imposed stress under a corrosive environment. Almost all the materials used in geothermal power plant equipment are subjected to static or cyclic stress simultaneously with corrosion action. Therefore, superimposing of the chemical corrosion action caused by the hydrogen sulfide and chlorine ions under the existence of moisture in geothermal steam and static stress may cause stress corrosion cracking. Since high strength steel and austenitic stainless steel are highly susceptible to stress corrosion cracking, this is an important test for the geothermal power plants in which a large amount of these materials are used.

3 Corrosion fatigue test

This test checks the fatigue strength of material in a corrosive environment. The pitting, intergranular corrosion, and other defects produced on the surface of materials under a corrosive environment become notches and lower

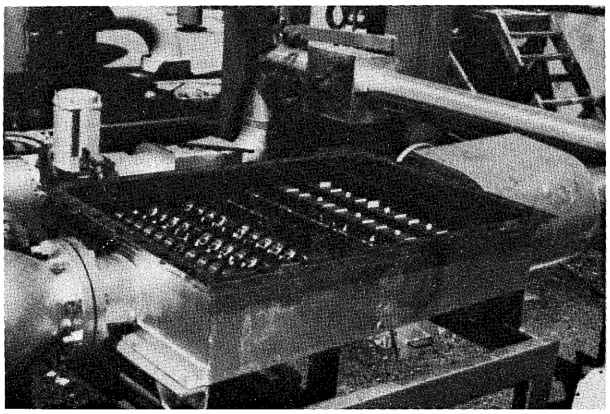


Fig. 17 Low speed steam test chamber

Table 2 Corrosion test plan at Ahuachapan P/S, El Salvador

Material \ Environment / Test item	Low velocity steam			Condensate			Moisture separator drain				Circulating water			Aerated condensate		High velocity steam
	C	F	SCC	C	F	SCC	C	T	F	SCC	C	T	SCC	C	SCC	E
CrMoV steel	○	–	○	○	–	○	–	–	–	–	–	–	–	○	–	–
NiCrMoV steel	○	–	○	○	–	○	–	–	–	–	–	–	–	○	–	–
Carbon steel	○	–	–	○	–	–	○	○	–	–	–	–	–	○	–	–
Carbon steel + epoxy resin coating	–	–	–	○	–	–	–	–	–	–	–	–	–	○	–	–
13% Cr steel	○	○	○	○	○	○	○	○	○	○	–	–	–	○	○	○
Same as above (hardened)	○	○	○	○	○	○	○	○	○	○	–	–	–	○	○	○
Same as above + silver brazed stellite	○	–	○	○	–	○	○	○	–	○	–	–	–	○	○	○
13% CrAl steel	○	–	○	○	–	○	○	○	–	○	–	–	–	○	–	–
Low C 18% Cr 12% Ni 2.5% Mo steel	–	–	○	○	–	○	–	–	–	–	○	○	○	○	○	–
Low C 18% Cr 8% Ni steel	–	–	–	–	–	–	–	–	–	–	○	○	–	–	–	–
18% Cr 12% Ni 2.5% Mo steel	–	–	–	–	–	–	–	–	–	–	○	○	–	–	–	–
Cast iron	–	–	–	–	–	–	–	–	–	–	○	○	–	–	–	–
Cast iron + epoxy resin coating	–	–	–	–	–	–	–	–	–	–	○	○	–	–	–	–
Cast iron + rubber coating	–	–	–	–	–	–	–	–	–	–	○	○	–	–	–	–
18% Cr 8% Ni Nb steel	○	–	–	○	–	–	○	–	–	–	–	–	–	○	–	○

C: Corrosion F: Corrosion fatigue SCC: Stress corrosion cracking T: Tensile strength E: Erosion the fatigue strength of the material. Therefore, the fatigue strength is very important for the parts such as turbine blades that are subjected to cyclic stress in the geothermal steam. Since the application of cyclic stress to material under an actual corrosive environment is difficult, a test piece corroded by exposing it to the geothermal fluid in advance is fractured by subjecting it to repeated stress in the atmosphere at this test.

4 Tensile strength test

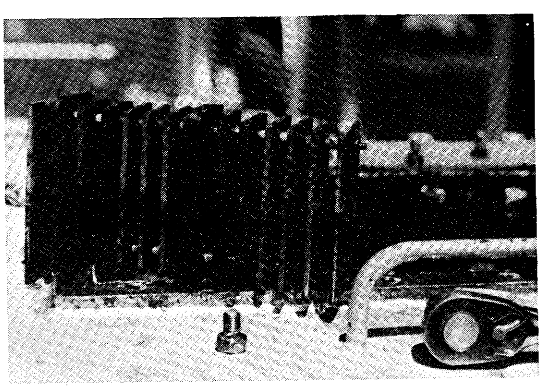
This tests finds the tensile strength of a test piece that has been corroded by exposing it to the geothermal fluid.

5 Erosion test

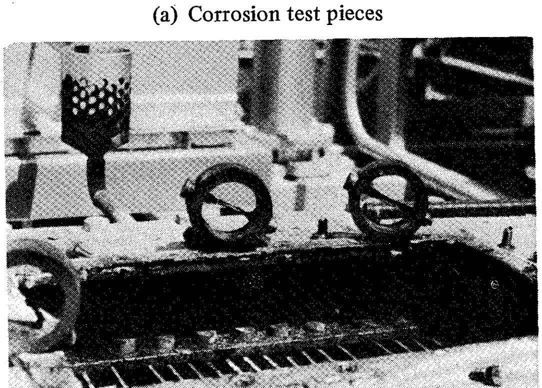
This test is performed to check the erosion caused by the drain and solid particles in the geothermal steam. The material of the turbine blades used in high velocity wet steam is subjected to this test. *Table 2* shows the combinations of the mateirals, test environment, and kinds of tests. *Fig. 17* shows a typical test chamber with the test pieces installed. This chamber is for low velocity steam.

(3) Test results

As the first stage of the tests, the test pieces were exposed to the test environment for 3 or 6 months. The present tests are scheduled to be continued.for one year as the second stage. Many significant results were obtained from these tests. We select the materials of the actual equipment and guarantee their reliability based on the results of these tests. *Fig. 18* shows the test pieces after exposure and *Figs. 19* and *Table 3* show the turbine blade material corrosion fatigue test results and the comparison of corrosion rate of the materials.



(a) Corrosion test pieces



(b) Stress corrosion cracking test pieces

Fig. 18 Test pieces after exposure

2) Laboratory corrosion test

This test was performed in an laboratory under the environment simulating the actual geothermal fluid. The natural environment cannot be completely simulated, but laboratory tests are advantageous in that such test as an acceleration test that emphasizes the corrosion effect can be performed under a controlled environment and are used in relative evaluation or preliminary selection of materials.

Fig. 20 shows the stress corrosion cracking test device used at our Kawasaki Factory as an example of this kind of test. *Fig. 21* is an example of the results of the stress corrosion cracking test on the 13% Cr steel used as the turbine blade material performed by using this test equipment.

Fig. 22 shows the corrosion fatigue test device installed at the Fuji Electric General Research Laboratory. This device was used to test the corrosion fatigue strength of the material by applying repeated stress to a test piece in a circulating liquid in which hydrogen sulfide was dissolved to simulate the geothermal fluid. *Fig. 23* shows a typical test result. It can be seen from this test result that the fatigue strength of material in a corrosive atmosphere is about one-half of that in air.

2. Condenser model test

Since the condensate does not have to be recovered at a geothermal power plant, it differs from an ordinary

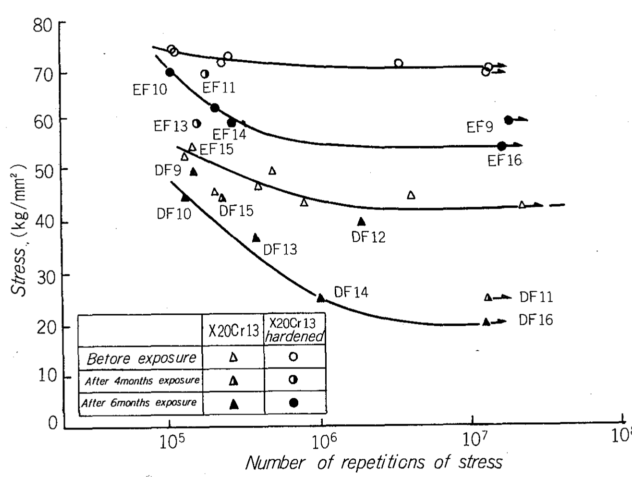


Fig. 19 S-N diagram of 13% Cr steel exposed to condensate

Table 3 Corrosion rate of material (unit: mm/year)

Material	Test environment	
	Steam	Condensate
CrMoNiV and CrMoV steel	0.133	0.219
NiCrMoV steel	0.123	0.242
Carbon steel	0.159	0.228
13% Cr stainless steel	0.008	0.0003
Stainless steel Type 405	0.033	0.0003
Stainless steel Type 347	0.003~0.006	0.0003
Stainless steel Type 316L		0.00005

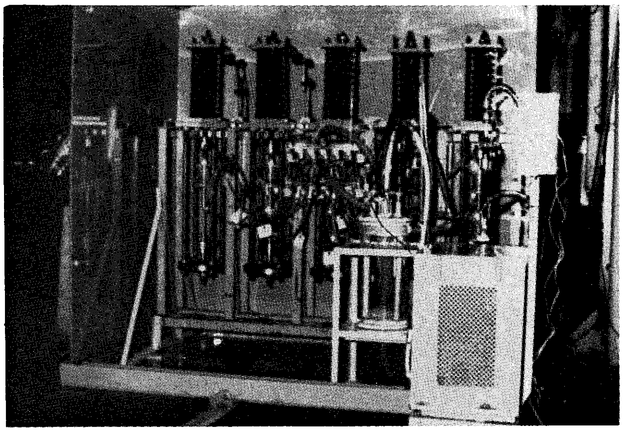


Fig. 20 Stress corrosion cracking test device in laboratory

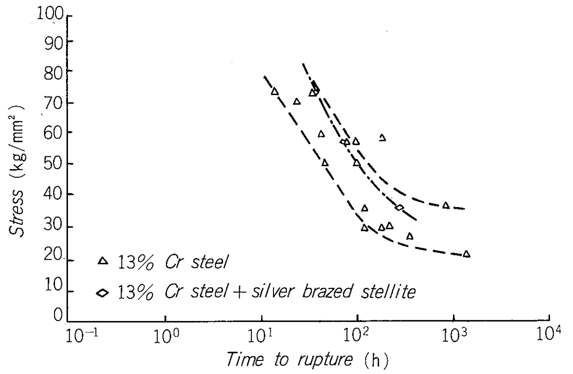


Fig. 21 Test results of stress corrosion cracking test on 13% Cr steel

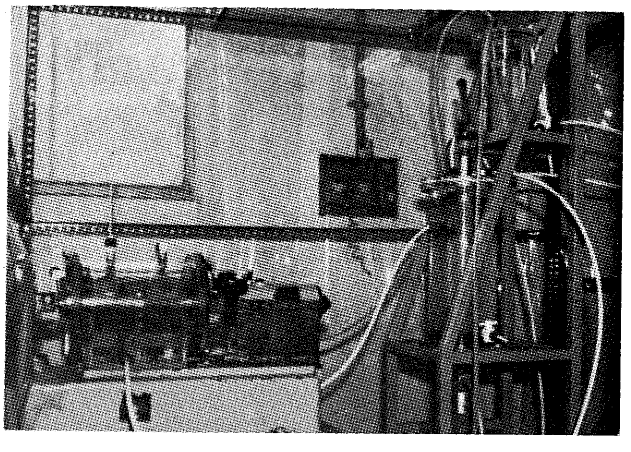


Fig. 22 Corrosion fatigue test device in laboratory

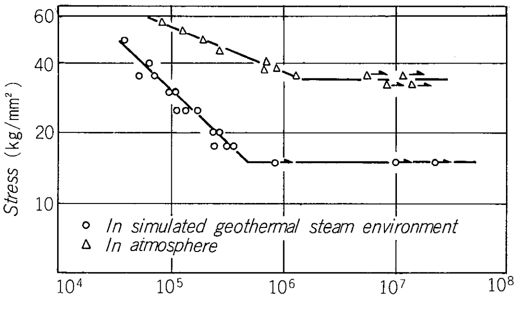


Fig. 23 S-N diagram of 13% Cr steel under corrosive circumstances

thermal power plant and a direct contact type condenser is often used. Moreover, since the geothermal steam flowing into the condenser contains a large amount of non-condensable gas as previously menthined, adequate consideration must be given to handling of this gas so that the condenser will display the specified performances. We have conducted various tests to solve these problems unique to the condenser of geothermal power plants. The following outlines these tests.

1) Water spray nozzle spray test

We adopt a spray type direct contact condenser. To realize an economical condenser that display high performance at a lower power consumption, a spray nozzle that provides a good spray at a low spray pressure and a large amount of cooling water per nozzle is demanded. To satisfy this demand, we performed various spray tests and developed a spray nozzle having a unique construction. *Fig. 24* shows the spray test of nozzle for the condensing zone and *Fig. 25* shows a cross section of the spray nozzle. Cooling water is sprayed in two parts, one is from inner discharge and the other from outer discharge with swirl.

2) Examination of influence of gas content on heat transmission at the condensing zone

Geothermal steam contains large amount of non-condensable gases such as carbon dioxide, hydrogen sulfide, etc. These gases together with the air, which is contained in the cooling water and also which leaks into turbine and condenser, obstruct the heat transmission at condensing zone and worsen the vacuum. The degree of this obstruc-

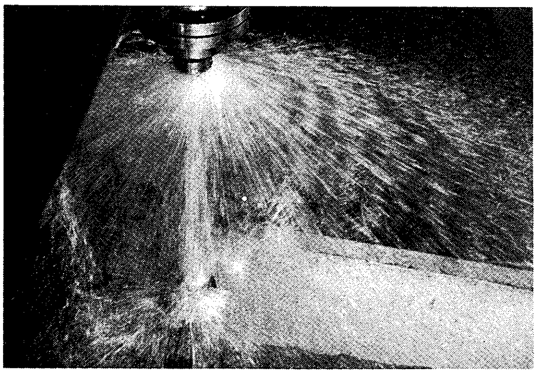


Fig. 24 Spray test of nozzles for condensing zone

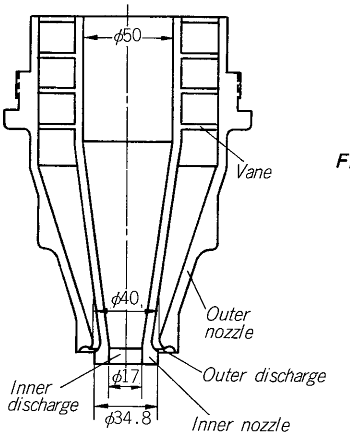


Fig. 25 Spray nozzle for condensing zone

tion and worsening varies with the gas quantity and condenser construction. To clarify this relation, we performed tests using a model condenser. *Fig. 26* shows the test device and *Fig. 27* shows the relation between the gas contents and the non-dimensional temperature rise in the condenser. The closer this value is to 1.0, the smaller the difference between the cooling water outlet temperature and the saturation temperature of steam is. In other words, a higher vacuum can be obtained.

3) Examination of influence of gas content at the gas cooling zone

After most of the steam has been cooled and condensed, in the condensing zone the remaining steam and non-condensable gas flow to the gas cooling zone where the volume is reduced by condensing further a part of the steam and the mixture of steam and gas is led to gas extractors. The more the cooling of mixture at gas cooling zone is, the smaller the volume of it becomes and the capacity of the gas extractor can be made small. Therefore, the performance of the gas cooling zone is an important factor governing the performances of the total condensing system facility, and since this must be clearly elucidated. By using a model of the gas cooling zone, various tests were performed and the performances were analyzed. *Fig. 28* shows the test equipment and *Fig. 29* shows the relation between the

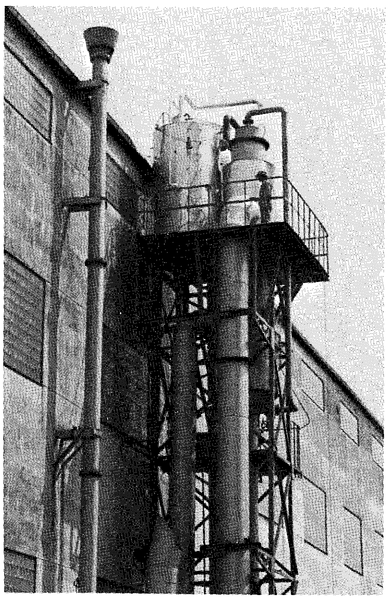


Fig. 26 Model condenser, condensing zone

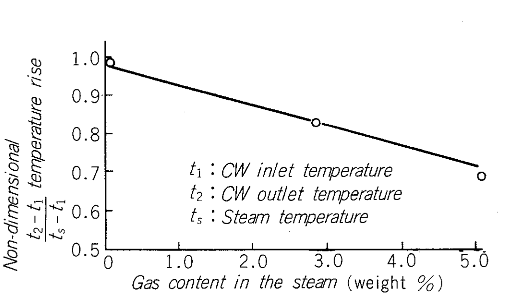


Fig. 27 Relation between gas content and condenser pressure

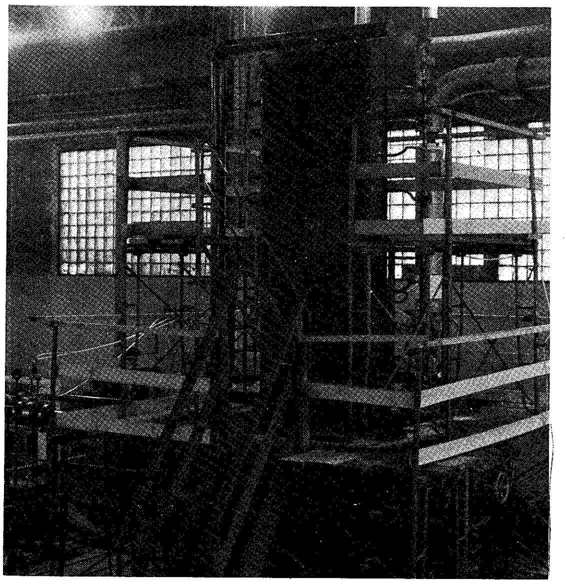


Fig. 28 Model condenser, gas cooling zone

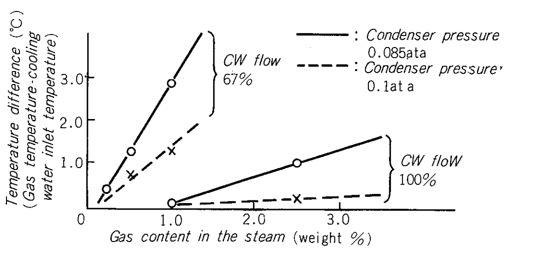


Fig. 29 Relation between gas content and exhaust gas temperature

gas content and exhaust gas temperature.

IV. CONCLUSION

The oil crisis made the era of abundant cheap oil a thing of the past, and many countries of the world are now promoting the development of technology to use solar energy, geothermal energy, wind power, etc. as alternative energy sources to replace the oil which currently occupies the major portion of the energy supply sources. Since a large amount of energy can be easily obtained from geothermal energy as heat and electric power converted from this heat, geothermal energy will probably occupy an important part as a new energy source in the future. Japan is a prominent volcanic country and its potential of geothermal energy is estimated to be equivalent to 40,000 MW of electric power. The Government's General Energy Committee estimates that the total capacity of Japan's geothermal power plants will reach 1,000 MW by 1985, 3,500 MW by 1990 and 7,000 MW by 1995.

Fuji Electric will continue its research and development in this field to supply more reliable and econominal plants to the world bearing the importance of geothermal energy as an new energy source in mind.