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MODERNIZATION OF LARGE KAPLAN RUNNER (UPDATING OF U.S. WELLS HYDROELECTRIC PROJECT)

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1. FOREWORD

The steady decrease in the number of new economically feasible hydroelectric power plant development regions is an international trend. Restrictions on the construction of new hydroelectric power plants are also becoming larger from the standpoint of environmental problems. Under these conditions, rehabilitation projects for old hydroelectric power plants are increasing. These projects are designed to increase annual power output by increasing efficiency on power plants whose efficiency has deteriorated due to aging and whose maintenance and repair are costly and time consuming. They also intended to make maintenance easy and cheap. Fuji Electric has participated in rehabilitation projects from an early stage. The rehabilitation conditions of the 10 large Kaplan runners for the Washinton state Wells Hydro electric Project are introduced and their features described.

The Wells Dam Hydroelectric Project is one of many large hydro power projects constructed by damming the Colombia River, one of the largest rivers in the United States. Ten generating units were installed, each driven by a 97,900kW, direct-connected Kaplan turbine with a 7.4m diameter runner. The existing turbines were manufactured by a U.S. company. The first unit started operation in 1967.

Fig. 1 Wells Dam Wells Dam Hydroelectric Project

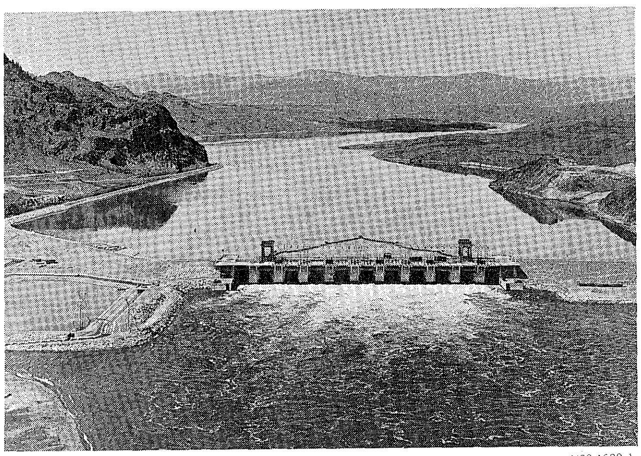

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Table 1 Wells Dam Hydroelectric Project

(a) Turbine

Type		Vertical shaft Kaplan turbine	
Output	(kW)	Maximum	Rated
		97,900	89,500
Head	(m)	22.86	19.5
Rotating speed	(rpm)	85.7	
Runner diameter	(mm)	7416.8 (existing unit design value)	
Number of runner blades		5	
Number of units		10	

(b) Generator

Type		Vertical shaft synchronous generator	
Capacity	(kVA)	Maximum	Rated
		93,725	81,500
Voltage	(kV)	14.4	
Rotating speed	(rpm)	85.7	
Number of units		10	

A bird's eye view of the Wells Dam Hydroelectric Project is shown in *Fig. 1*. The specifications of the turbine and generator are listed in *Table 1*.

2. WELLS DAM HYDROELECTRIC PROJECT REHABILITATION PROJECT

This electric power plant was designed and commenced operation as Kaplan turbine on the original plan. However, from 1982, nine of the 10 units were compelled to operate as propeller turbines with fixed runner blades because of the increased link mechanism friction due to deformation of the runner hub and because the capacity of the runner servomotor was insufficient due to space restrictions. Thereupon, a project for making the runner blades adjustable by rehabilitating the runners of all 10 units and raising turbine efficiency and increasing the annual power output by introducing the newest technology was established.

The shift to execution of this project used the following internationally unique techniques.

(1) Stage 1

Selection of two companies by overall evaluation of performance, model turbine development time, cost, etc. by international tender. Fuji Electric and an Austrian company were selected by this method.

(2) Stage 2

Independent development of the optimum model for this power plant over one year by both companies. Backed by a computer and the newest measuring instruments, Fuji Electric quickly developed a model with excellent performance as described in detail below.

(3) Stage 3

Verification test for efficiency, cavitation, and other performance of the models developed by the both companies in an independent hydraulic laboratory in Swizerland. Strict medium level verification tests spanning two months each made it clear that the performance of the Fuji Electric mode exceeded those of the Austrian company in all aspects.

(4) Stage 4

Selection of the company to undertake this rehabilitation project from the results of these model tests. Fuji Electric was selected to manufacture, install, and test the 10 large Kaplan runners in this way.

3. DEVELOPMENT OF NEW RUNNER

3.1 Characteristics of existing turbine

Since the existing Kaplan turbine was designed more than 20 years ago, it is different from current standard Kaplan turbines and has numerous disadvantages from the standpoint of performance. The main points are:

(1) The distance from the bottom end of the wicket gates to the runner inlet is short and the radius of curvature of the side wall is also small. Therefore, an unbalanced flows into the runner due to the curvature of the meridional flow channel.

(2) When the wicket gate opening is large, the trailing edge of the wicket gate is protrudes and projects into the Passage. Therefore, a large wedge-shaped the bottom of the wicket gate and the outside edge of the runner.

(3) Since the discharge ring is not spherical, but cylindrical, when the runner blade opening is large, the gap between the discharge ring and the outside edge of the runner becomes large near the runner blade inlet and outlet.

(4) From the standpoint of power station operation, the maximum output discharge must be much larger than that at the maximum efficiency point and maintaining high efficiency at the maximum output point is diffcult.

These characteristics of the existing turbine not only limit the shape of the new runner in the development process, but also have a large effect on flow around the runner, that is, turbine efficiency, after rehabilitation.

3.2 Study of runner inlet flow

To achieve a substantial improvement in performance by rehabilitating the runners of the existing turbine as described above, the water flow inside the turbine must be determined in detail and a runner most suitable for this water flow must be designed. Therefore, the water flow was analyzed by the quasi-three dimensional method and was measured with a laser two focus velocimeter (L2F). This L2F has the focus of a laser beam between two adjacent points in a fluid and measures the time required for micro particles to pass between these two points. The flow of a fluid can be determined by analyzing this data by statistical techniques.

The meridional section shape of the pertinent turbine and the water flow analysis region are shown in *Fig. 2*. The affect of the previously mentioned gap between the bottom of the wicket gate and the outside edge of the

Fig. 2 Water flow analysis region

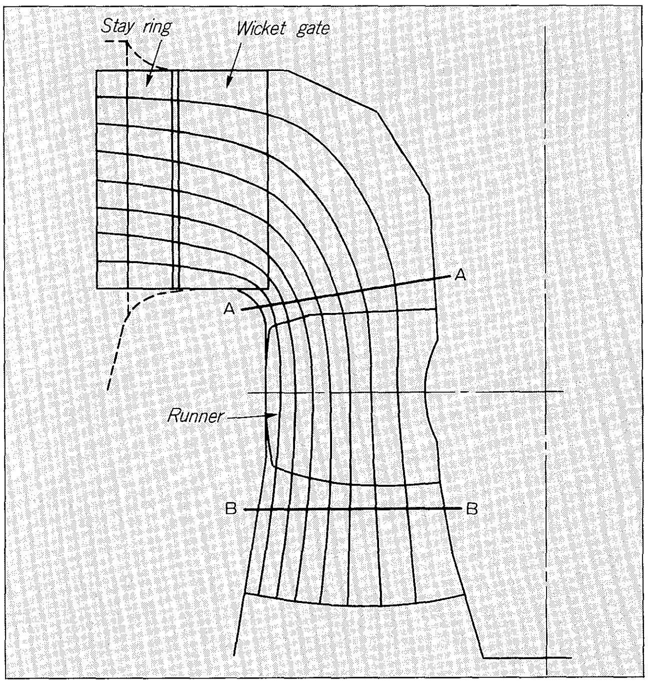


Fig. 3 Laser two focus velocimeter

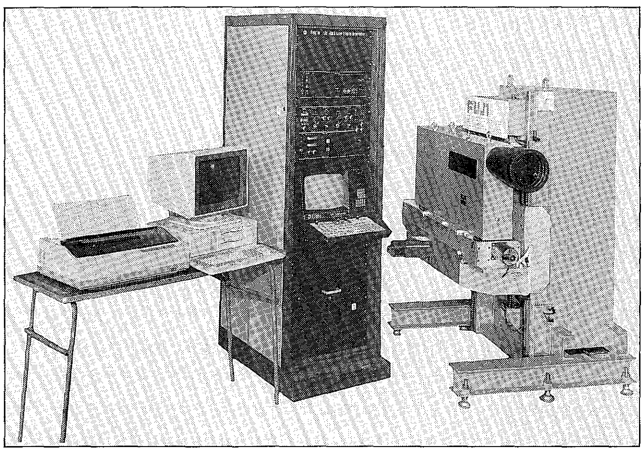


Fig. 4 Runner inlet velocity distribution

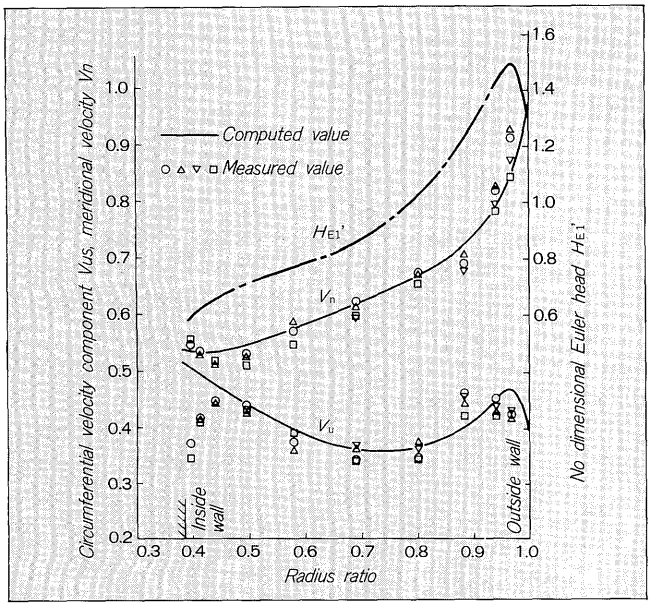


Fig. 5 Runner outlet Euler head distribution

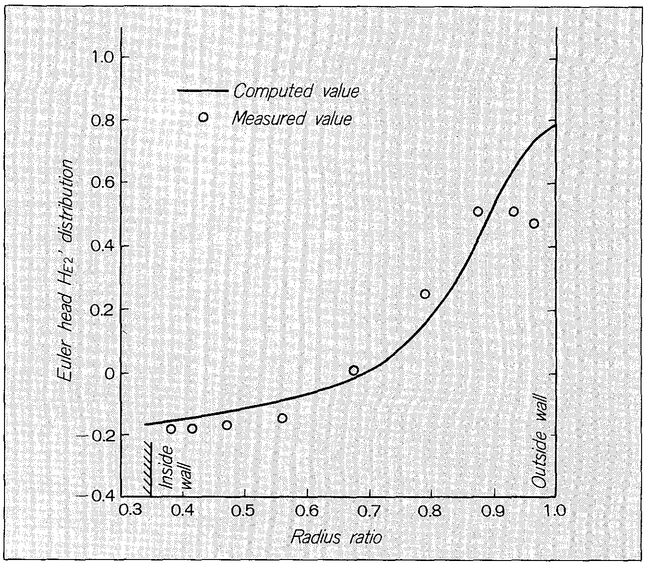
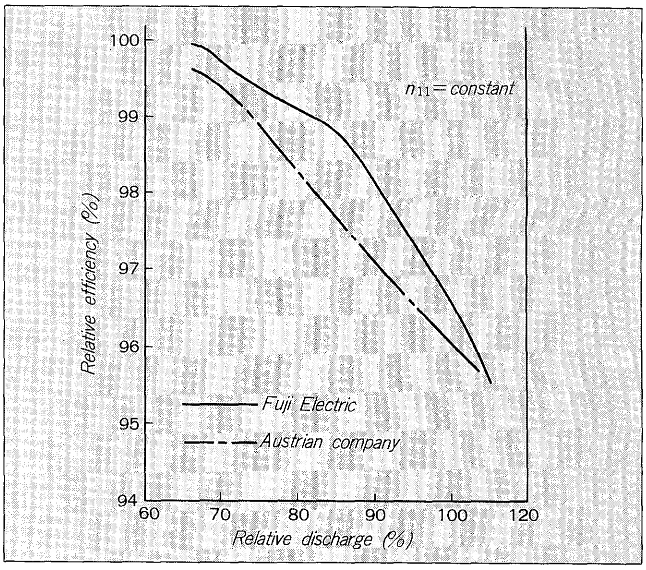


Fig. 6 Model efficiency curves



runner is indicated approximately in the computation. The water flow was measured with a 340mm runner diameter model turbine on an air test stand and using a 10μm focus diameter, 280μm distance between focuses L2F. A photograph of the L2F is shown in *Fig. 3*.

Figure 4 shows the runner inlet (A-A) velocity distribution and circulation distribution at the rated output point in the form of a no dimensional Euler head ($H_{E1}' = UV_U/gH$). The solid lines in the figure are the result of water flow analysis by computer and the four kinds of symbols are the result of measurement by L2F.

U in *Fig. 4* represents the peripheral velocity component, V_U represents the circumferential velocity component, and V_n represents the meridional velocity component perpendicular to the A-A section. Except for near the walls, the water flow analysis result and measured result are in good agreement.

The curvature of the meridional flow passage has a strong affect on the flow past the wicket gate. V_n is large at the outside wall corresponding to the inside of the curvature. Since the velocity increases toward the bottom of the wicket gate, a strong swirl is created and it was found that the runner inlet H_{E1}' distribution tilts noticeably toward the outside. The characteristics of the fived part of the existing turbine were decided quantitatively from these analysis results.

3.3 Design of new runner

The new runner was designed as the most important subject in achieving high efficiency. To realize high efficiency, the runner load distribution must be made as uniform as possible in the radius direction. However, since the discharge ring is cylindrical as previously described, when the runner blade opening becomes large, a greater gap is created between the outside edge of the runner and the discharge ring. Therefore, when a large load is applied near the end of the blade, the leakage flow increases and causes a drop in efficiency and severe cavitation. The runner blade was shaped so that a minimum gap is maintained at the end of the blade over the normal operating range.

From the fact that the Euler head H_{E1}' distribution of the new runner outlet (B-B section of *Fig. 1*) shown in *Fig. 5* is almost the same shape as the H_{E1} distribution, it can be seen that the runner load distribution ($HR = H_{E1}' - H_{E2}'$) is almost constant.

Besides these, cavitation, water pressure fluctuation, etc. were analyzed and verified and a high performance runner was developed in one year.

3.4 Model test results

An independent hydraulic laboratory in Switzerland performed official model tests from Octorber to March 1987. The new Fuji Electric runner exhibited better efficiency, reduced cavitation, water pressure fluctuation and all other performances than the runner made by the Austrian company. The results of the efficiency test are shown in *Fig. 6*.

4. MACHINE STRUCTURAL DESIGN

4.1 Large movable blade runner

The runner of this power plant is one of the largest movable blade runners in the world and has five blades, an outside diameter of 7.4m, and weight more than 100 tons. Although the plant is operated at a high load, during operation, load changing (opening changing) are frequent and each part of the runner must maintain a margin of strength and stiffness.

However, on the other hand, except for the runner, the existing parts and ancillary equipment are used and there are many restrictions for runner design and manufacture.

Therefore, for the design and manufacture of the actual runner, the newest Fuji Electric design and analysis technology, including structural analysis by the finite element method and CAD/CAM (Computer Aided Design/ Computer Aided Manufacture), were used and the connection method with existing parts and the assembly, shipment, and installation methods unique to this project were repeatedly studied based on our abundant achievements.

4.2 Runner internal structural design

Generally, a large movable blade runner servomotor is installed in the runner hub and arranged at the above or below of the blade shaft. In runner internal structural design, ample capacity of the servomotor, which operates the runner blades, and the strength and rigidity of each part are important points under the hydraulic ristriction with runner configuration.

On the other hand, making the runner hub thickness that is the most important in securing strength and stiffness and space for the servomotor and its operating mechanism have an alternative problem. Therefore, sophisticated technological power that balances these design elements at a high dimensions is necessary in runner structural design.

The structure of the new and old runners is compared in *Fig. 7*.

The old runner has the servomotor above the blades, but the new runner uses the Fuji Electric standard construction with the servomotor below the blades the shaft to improve strength, stiffness and increase in servomotor capacity.

Ample runner blade and runner hub strength and stiffness are obtained by optimizing the thickness of each part and the addition of reinforcing ribs by structural analysis using the three dimensional infinite element method.

In runner blade structural analysis, the nonlinearity of the hub bearing is referenced and cyclic symmetry analysis that takes the circumferential asymmetrical load is performed by hub and blade trunnion integrated model. The results of these analyses are shown in *Fig. 8* and *Fig. 9*.

Not only the hub and blade trunnion unit strength and stiffness, but the affect of their deformation on the link mechanism, servomotor, and other moving parts were also studied and the suitable bearing gap, as well as the shape and dimensions of the parts with no high local stress. were decided by this means. The fatigue strength of each part was also amply studied by applying the results

Fig. 7 New and old runners sectional view

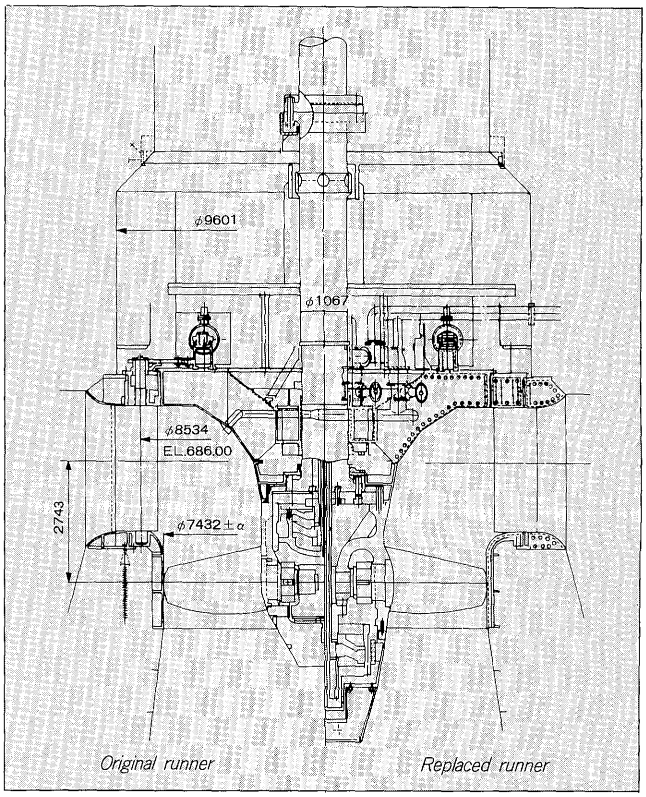


Fig. 8 Result of stress analysis of runner hub by finite element method

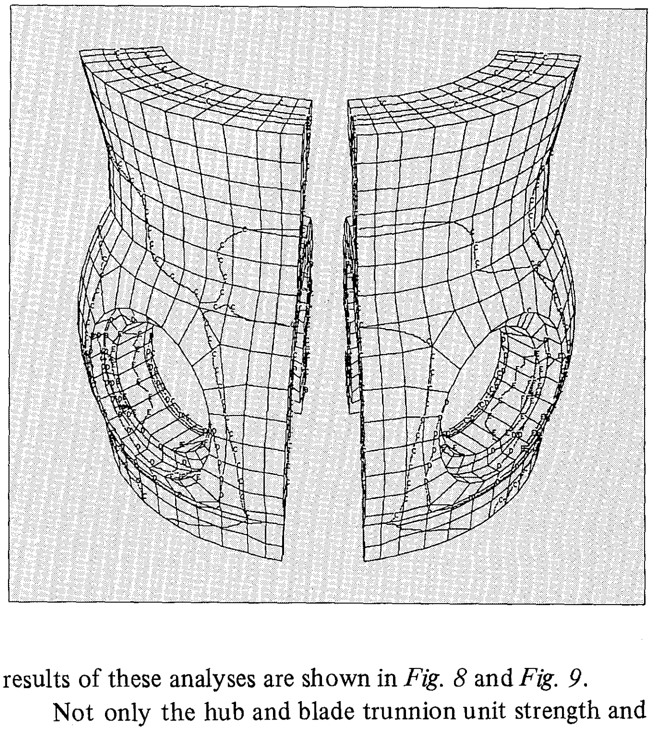
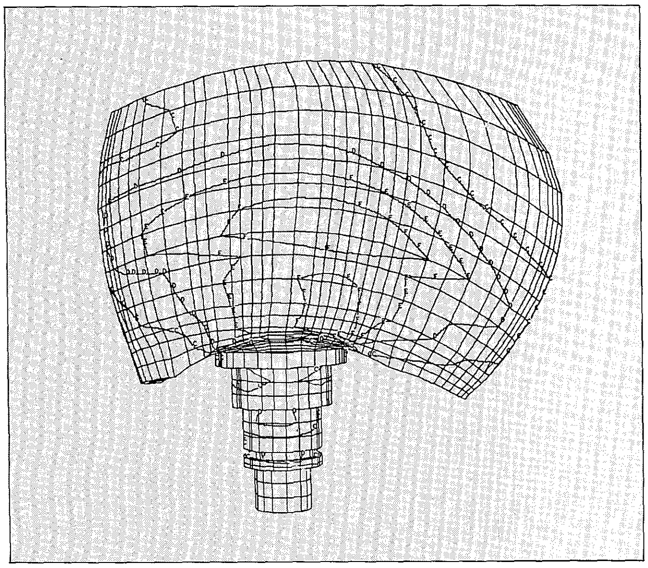


Fig. 9 Result of stress analysis of runner plate by finite element method



of finite element method stress analysis and an appropriate material was selected.

4.3 Matching and connection with existing parts.

The existing shaft, turbine guide bearing, Kaplan device, oil supply pipes, discharge ring, etc. are used.

The oil head device is installed at the top of the generator and hydraulic pressure is sent to the inside of the runner servomotor by integrated oil supply pipes that pass down the center hole of the shaft. With the old runner, the integrated oil supply pipes, which are about 20m, long was constructed so that the weight was supported by the servomotor. However, with the new runner, modification of the runner structure, especially movement of the servomotor to the bottom of the shaft, required modification of the oil supply pipe support method and conscientious study of the affect of the shaft system on the vibration characteristic.

Therefore, detailed shaft system eigen value analysis was performed and it was verified that the structural modifications had no adverse affect on the existing parts.

Since the existing discharge ring was made of ordinary steel instead of stainless steel, it was damaged by erosion, cavitation pitting, etc. even though it was repaired . This damage makes the runner peripheral gap nonuniform and leads to a drop of efficiency. Therefore, the discharge ring inside diameter of each unit was measured and studied by using a special measuring device beforehand. As a result, it was evident that the discharge ring is not a trudy circulous, but has a difference average diameter for each unit.

Therefore, the optimum repair method and the cost, etc. required for repair, were studied by using a computer based on the measurement data. As a result, repair was made by grinding and a runner diameter with the lowest repair cost for each unit was selected.

In this way, matching and connection with the existing parts, which are the most important and most difficult problems in a rehabilitation project, were seriously studied by using our experience with rehabilitation projects to the full.

5. RUNNER MANUFACTURE, SHIPMENT, AND INSTALLATION

The runner is a large type with a diameter of 7.4m and gross weight of over 100 tons. Its manufacture and assembly at the factory were backed by large numerically controlled machine tools. The runner undergoing a dynamic balance test after overall assembly at the factory is shown in *Fig. 10*.

Because of its large size, the runner could not be shipped fully assembled and after factory assembly and testing, it was disassembled into components and shipped and reassembled at the size.

Since on-site reassemble and testing are performed under a severe environment which reaches 20°C below freezing in the winter, besides dimension control of each part, assembly tests of the packings at low temperature were performed during manufacture and testing at the factory.

On-site installation work was performed with interval of less than 3 months between units. Installation of all 10 runners was a tremendous job requiring about three years. During this time, assembly of new runners that were disassembled and shipped and disassembly of the old turbine and generator proceeded simultaneously. Moreover, because of existing facility restrictions (building strength, crane capacity, etc.), this work had to be performed in a restricted space. Therefore, conscientious studies and consultations on the assembly, installation, and test procedures were conducted with the customer and installer and the process was reduced by completing the jigs and tools. *Fig. 11* is a photograph of the new runner assembled with the old top cover at the site.

Fig. 10 Runner under dynamic balance test (factory)

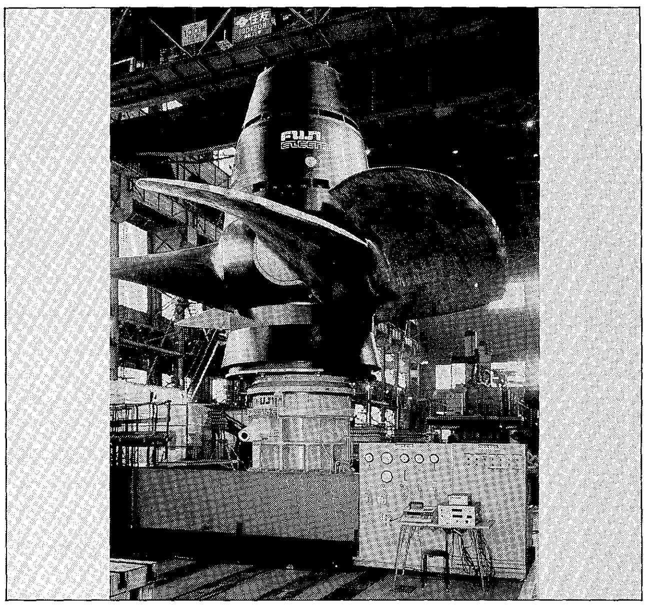


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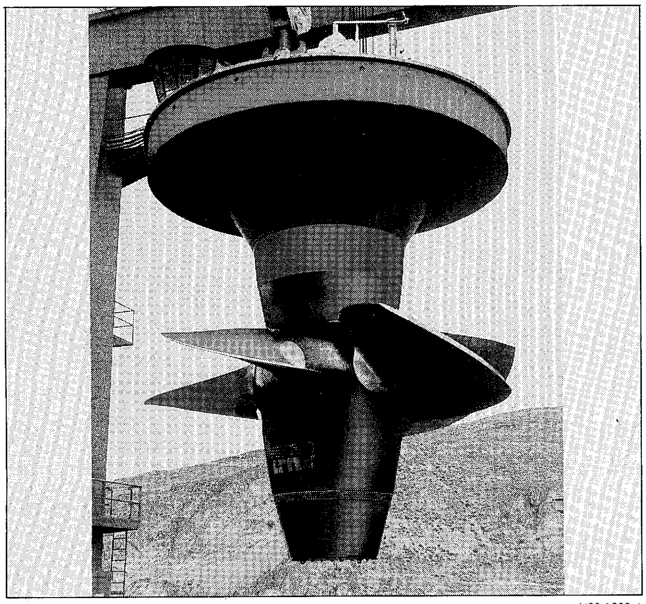
Fig. 11 Inserted runner (site, integrated with old top cover)



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6. CONCLUSION

Installation and testing of the first unit was completed and commercial operation began in March 1988. Factory work was completed with the shipment of the tenth runner in March 1990. Completion of installation and testing of the tenth unit is forecast for July 1990.

As previously mentioned, rehabilitation of existing aging hydroelectric power plants is excepted to increase in the future. The authors will be happy if this material serves in the planning of these projects.