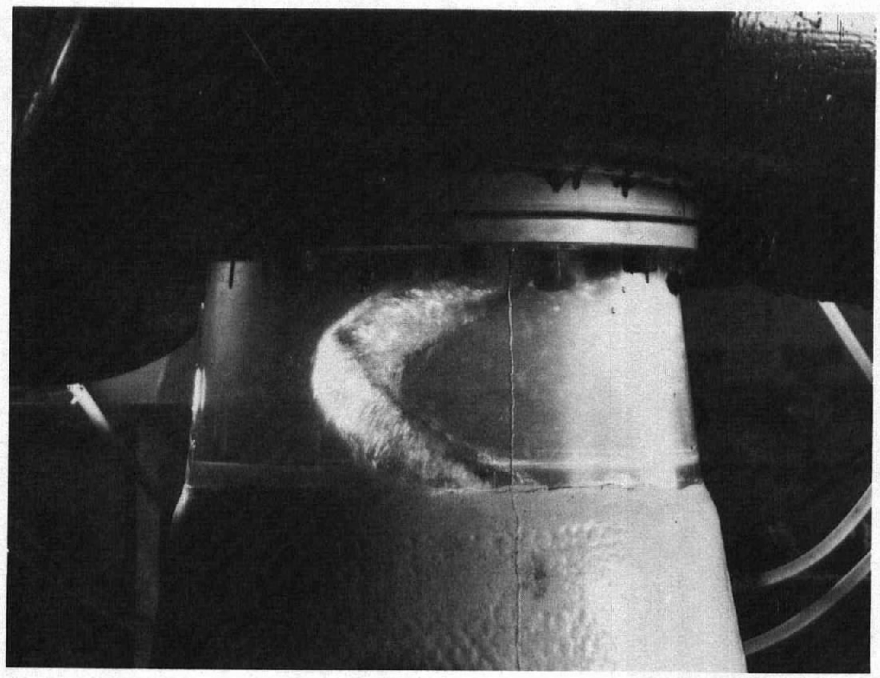
R-91-11

# EVALUATION OF TECHNIQUES FOR DETECTION OF CAVITATION ON THE RUNNER OF A MODEL HYDRAULIC TURBINE



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Morris M. Skinner and Tony L. Wahl


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16. ABSTRACT

The Bureau of Reclamation's 9-inch turbine model test stand was moved in 1988 from Estes Powerplant to the Engineering Research Center at Colorado State University to conduct research on detecting cavitation on the model turbine runner. Details of the installation are provided, and operating procedures are described. Following installation and the completion of checkout tests, research was conducted on four techniques to detect cavitation on the runner of the model turbine. The investigations included: (1) narrow band and one-third octave analyses of hydrophone, accelerometer, and pressure transducer output; (2) acoustic emission; (3) shaft torque transducers; and (4) the use of magnetostrictive sensors. Hydrophone, accelerometer, and pressure transducer outputs have been related to the cavitation index. Experiments conducted with acoustic emission equipment indicated that additional research should focus on sensors attached to the shaft of the turbine. A prototype shaft torque transducer was developed that may be useful in a variety of field test conditions. Magnetostrictive sensors have shown promise as highly sensitive cavitation detection devices that may obtain signals directly from the shaft of a hydraulic turbine.



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# Evaluation of Techniques for Detection of Cavitation on the Runner of a Model Hydraulic Turbine

by

**Morris M. Skinner**
**Tony L. Wahl**

Hydraulics Branch
Research and Laboratory Services Division
Denver Office
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Reclamation's shops personnel at Estes Powerplant disassembled the turbine test stand and packed it for shipment to Fort Collins. Bob Brennan, Kerry Sheaman, and Gale Murphy performed the majority of the installation work at Colorado State. Gerald Hiett and Dan Drake helped locate important drawings and documentation in Reclamation files. Dr. Henry Falvey provided valuable assistance throughout the relocation project. Tom Isbester and Brent Mefford helped with initial startup, checkout tests, revisions to operations checklists, and setup of data acquisition equipment.

Warren Frizell and Cliff Pugh reviewed this report and provided many excellent comments and suggestions. Barbara Prokop assembled the report and provided editorial review.

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# INTRODUCTION

Reclamation (the Bureau of Reclamation) and CSU (Colorado State University) have agreed to collaborate on cavitation research with a model hydraulic turbine. The turbine is a 1:40.33 scale model of the 700-MW turbine units G22, G23, and G24, at Grand Coulee Third Powerplant, Columbia Basin Project, WA. Allis Chalmers Corporation, York, PA, fabricated the model turbine, which was originally installed in the turbine test stand at Estes Powerplant, near Estes Park, CO, in 1974. The model is designed to operate in the prototype head range and provides complete geometric similarity with the prototype from the penstock intake through the downstream tailrace. Major components of the turbine model are shown in figures 1 and 2.

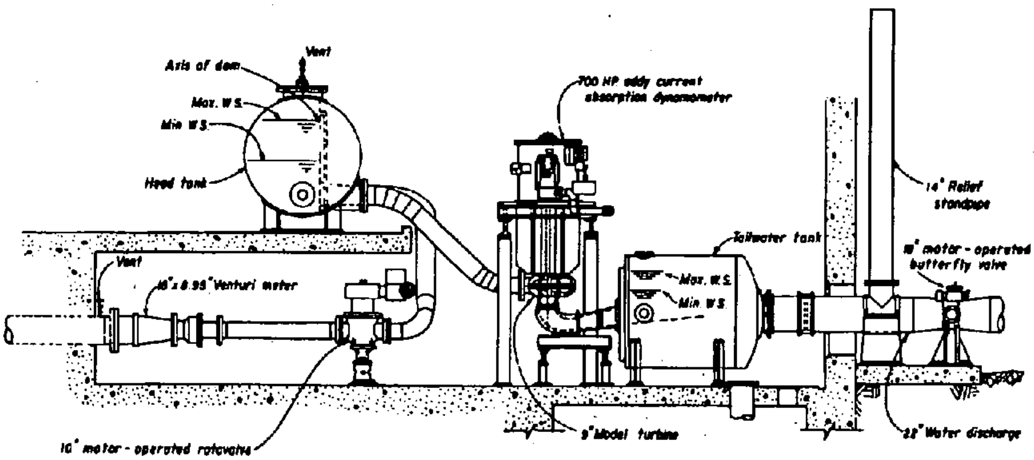



Figure 1. - Elevation view of the test stand, as it was installed at Estes Powerplant. The standpipe was moved about 60 ft downstream when the test stand was installed at CSU.

Reclamation used the turbine model during the 1970s and early 1980s for fundamental research on the phenomenon of draft tube surging. Following decommissioning of the test stand in 1985, the facility was moved to CSU, where the model could be used for cavitation and draft tube surging research. A summary of the major events in the relocation project is given in table 1.

The cooperative agreement had two main objectives. The first was the successful installation and operation of the turbine at CSU. The second was to investigate four techniques for monitoring the onset and severity of cavitation on the runner of a model Francis turbine. The four techniques are:

- Narrow band and one-third octave analyses of hydrophone, accelerometer, and pressure transducer output
- Analysis of AE (acoustic emission)
- Analysis of shaft torque transducer output
- The use of magnetostrictive materials to detect stress waves traveling on the turbine shaft

Each of these techniques demonstrated some potential for cavitation detection on prototype facilities. Controlled evaluation of these techniques can be most effectively accomplished using a scale model operating over a wide range of carefully controlled flow conditions in a laboratory environment. Once proven, these techniques could be applied to prototype machines.

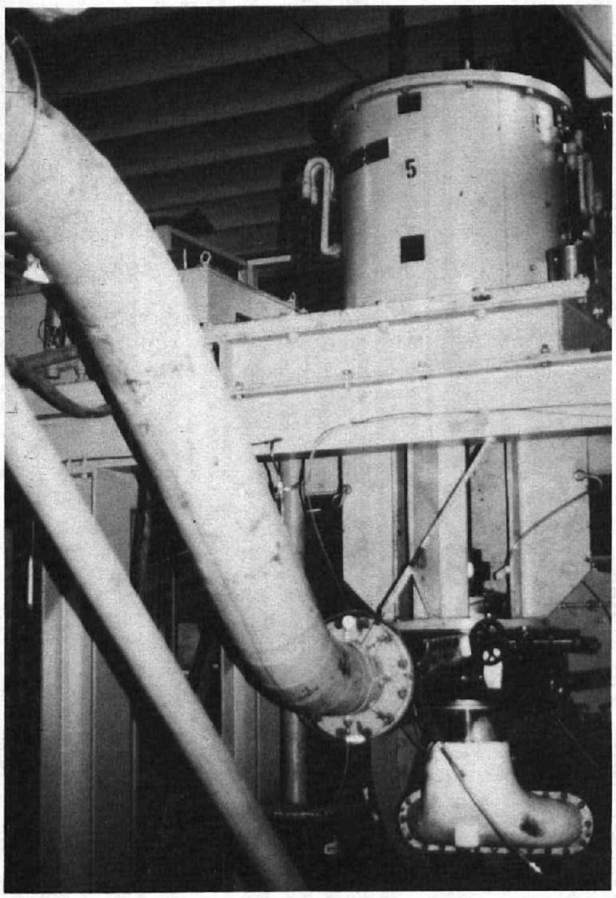


Figure 2. - The penstock and model turbine area. Main components shown include the penstock (left), spiral case, draft tube, and dynamometer (top).

Table 1. - Time sequence of major events

| | |
|---|---|
| 1-21-88 | Planning meeting in Loveland to discuss moving the turbine |
| 2-17-88 | Meeting at Estes Park to coordinate disassembly of the turbine |
| 4-88 | Arrival of turbine model at CSU hydromachinery laboratory |
| 6-8-88 | Official date of contract |
| 6-22-88 | Official go-ahead given to begin installation |
| 10-13-88 | Turbine, head tank, and tailwater tank in position |
| 11-3-88 | Steel frame anchored to floor and footings grouted |
| 11-10-88 | Cooling tank and associated piping in place |
| 11-17-88 | Installation of 18-in (45.7-cm) supply line for turbine |
| 11-29-88 | Installation of Rotovalve and venturi meter |
| 12-6-88 | Installation of butterfly valve and tailwater tank discharge piping |
| 2-7-89 | Purchase of new instrumentation |
| 2-24-89 | Completion of major electrical wiring installation |
| 3-1-89 | First site visit by Reclamation to evaluate progress |
| 3-23-89 | Site visit by Reclamation to prepare for turbine startup |
| 3-30-89 | Site visit by Reclamation to attempt turbine startup |
| 3-31-89 | Site visit by Reclamation first startup of turbine |
| 4-28-89 | Dynamometer disassembly started for inspection of bearings |
| 5-3-89 | Completed inspection of top bearings - dynamometer reassembled |
| 6-29-89 | Dedication ceremony |
| 6-30-89 | Cavitation detection research started |

## CONCLUSIONS

The model turbine was installed at CSU, and checkout tests were performed to ensure satisfactory operation. The completed turbine installation with the computer-aided data acquisition system provides a very useful facility for both graduate and undergraduate education. It is a unique installation for research studies in cavitation, draft tube surging, and other operational problems related to Francis-type turbines. The following groups of practicing engineers used the facility for short courses offered at CSU during the summer of 1989:

1. Second International Symposium on the Design of Hydraulic Structures.

2. International Association for Hydraulic Research Work Group on the Behavior of Hydraulic Machinery Under Steady Oscillatory Conditions.

3. The Egyptian Mechanical and Electrical Research Institute.

Three of the cavitation detection techniques identified on page 1 were tested using the model turbine. Tests were conducted to evaluate the sensitivity of magnetostrictive sensors using a prototype magnetostrictive device, separate from the operation of the turbine model. These investigations provided insight into the proper method and location for making measurements, the overall complexity of the cavitation process in hydraulic turbine, and directions for future research.

An operating hydraulic turbine produces a wide variety of waterborne, airborne, and structureborne vibrations of widely varying amplitude and frequency. The path (coupling) between the source of the signal of interest and the measuring transducer needs to be carefully evaluated and confirmed. Particular care should be taken in locating the transducer to reduce extraneous noise and increase the signal of interest. Additionally, measurement methods and locations must be compatible with field requirements and practicality.

Pressure transducers, hydrophones, and accelerometers are commercially available, dependable, precise measuring devices suitable for making measurements on hydraulic structures. One-third octave analyses of the output from all three of these devices showed an increase in output level with increasing cavitation activity on the runner. Plots of rms (root mean square) levels versus the cavitation index ($\sigma$) all indicated a break in slope that corresponded with the onset of cavitation in the vicinity of the runner.

One-third octave and narrow band analyses of the hydrophone output showed a definite drop in signal level above about 5 kHz as cavitation activity increases, i.e., as $\sigma$ decreases. This is the same effect noted in tailwater hydrophone measurements at Flatiron Powerplant. Cavitation generates bubbles that may attenuate the higher frequencies in a systematic way.

A pressure transducer mounted just below the runner in the draft tube wall served as a good indicator of cavitation activity. In addition to one-third octave rms levels, time domain output and narrow band analyses both gave some indication of cavitation. Attenuation of the bucket-passing frequency occurred as cavitation increased. The attenuating effect of the vapor cloud is apparently the cause.

One-third octave rms levels of the accelerometer output sampled between 12.5 and 20 kHz showed a definite increase with cavitation intensity. However, due to the mass damping at this frequency range, spikes on the time domain plot were absent. Very high frequency signals were detected at cavitating conditions. These signals indicate that a high-frequency response accelerometer, i.e., AE might be more appropriate.

Torque and torque variation measurements failed to provide direct indication of cavitation. Since the sampling rate was only once per revolution for the torque indicator in use, events affecting torque on a shorter time scale were not evident. Shaft oscillations were detected.

AE instrumentation was very responsive to a variety of signals originating in many parts of the turbine test stand. These included cavitation at the Rotovalve and air passing through the head tank and other portions of the system. Difficulty was experienced in isolating AE signals due to cavitation on the runner. Some insight into proper placement of AE sensors was obtained. This work indicated that sensors obtaining their signal directly from the shaft should be investigated further.

Experiments with a prototype magnetostrictive actuator provided valuable experience with basic concepts of magnetostriction. The actuator was very sensitive to small impact loads. Magnetostrictive materials have the potential to form the basis for a new class of highly sensitive, noncontact sensors. Additional work using both magnetostrictive composites and amorphous films (metallic glasses) is encouraged.

## RECOMMENDATIONS

The process of developing procedures for monitoring cavitation intensity on the runner of a working hydraulic turbine ideally would involve a machine (both model and prototype) where the cavitation activity was clearly visible. The Allis Chalmers 1:40.33 scale model affords an excellent view of the cavitation activity over at least the lower portion of the buckets. Cavitation occurring on or near the wicket gates or in other parts of the machine above the runner was not visible at the source. One of the Flatiron Power Plant units would provide a good field verification site for the model measurements if some viewing mechanism could be fitted to either units 1 or 2.

The transducer location for optimum coupling between the runner and detector appears to be the shaft; however, more study is required to confirm this. The use of magnetostrictive films attached to the shaft should be thoroughly investigated.

## TURBINE TEST FACILITY

The turbine test facility was installed in the hydromachinery laboratory at the CSU ERC (Engineering Research Center). Thelaboratory was built in the late 1960s to test large pumps, valves, and other hydraulic machinery. The floor of the laboratory is a continuous poured, 3-ft (0.91-m) thick, reinforced concrete slab, making the site ideal for vibration testing of large machinery.

Water supply to the model is provided through a steel pipeline directly from Horsetooth Reservoir, just west of the laboratory. The supply line begins at a valve house at the base of Soldier Canyon Dam, where a 36-in (91.4-cm) diameter pipe draws water from the bottom of the reservoir. This pipeline supplies water to the CSU hydraulics and hydromachinery laboratories, as well as Fort Collins Water Treatment Plant No. 2, located across Laporte Avenue north of the ERC. At the southwest corner of the hydraulics laboratory, a 36-in (91.4-cm) ball valve with a 6-in (15.2-cm) bypass serves as a guard valve for the hydromachinery laboratory. A 26-in (66.0-cm) pipeline continues 682 ft (208 m) to a trifurcation just south of the rainfall and erosion facility. The right-hand branch of the trifurcation is a 24-in (61.0-cm) diameter line that proceeds about 80 ft (24.4 m) to a valve house located 230 ft (70.1 m) upstream of the hydromachinery laboratory. A motor-operated 24-in (61.0-cm) ball valve at this location serves as a second guard valve for the installation.

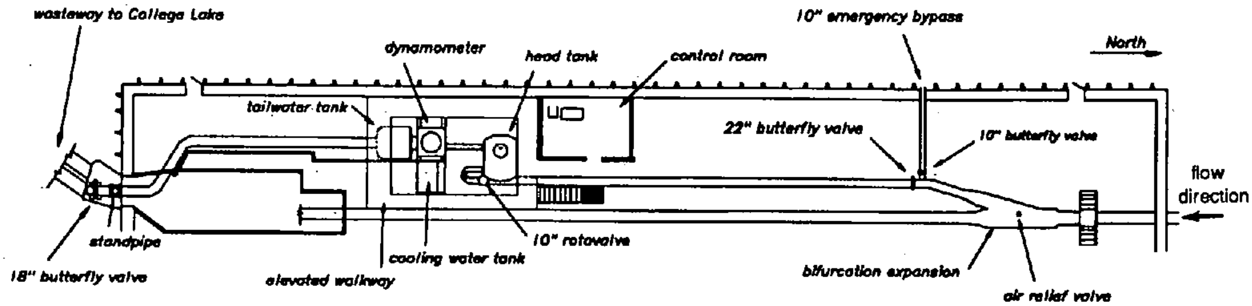



Figure 3. - Plan view of turbine test facility arrangement. The turbine test stand is installed on the west side of the hydromachinery laboratory at the ERC.

Following the guard valve, the pipeline enters the north end of the hydromachinery laboratory; the arrangement inside the laboratory is shown in figure 3. Just inside, the 24-in (61.0-cm) line enters a bifurcation, where the flow is diverted into the 18-in (45.7-cm) line supplying water to the test facility. An air-release, vacuum-break valve is mounted on the top of the bifurcation. Blowoff valves upstream of the bifurcation permit dewatering. Immediately downstream of the bifurcation a hand-operated 22-in (55.9-cm) butterfly valve is installed for emergency shutdown. A hand-operated 10-in (25.4-cm) butterfly valve controls a 10-in (25.4-cm) emergency bypass line, discharging through the west wall of the laboratory. The turbine test stand is located about 75 ft (22.9 m) downstream of this bypass. The facility from the venturi meter through the head tank, penstock, turbine, draft tube, and tailwater tank is essentially the same as it was at Estes Powerplant. The head tank rests on a steel frame structure about 8.5 ft (2.59 m) above the floor of the laboratory (fig. 4). The turbine, dynamometer, and cooling water tank are installed on the same steel structure used at Estes Powerplant (fig. 5). Discharge piping from the tailwater tank proceeds about 60 ft (12.2 m) downstream, through two 60° bends that align the flow for discharge past the standpipe, through an 18-in (45.7-cm) motor-operated butterfly valve, and into the wasteway. The wasteway conveys the discharge into an open channel leading to College Lake, about one-fourth of a mile downstream.

## INSTALLATION

### Control Room

The test facility is operated from a control room located on the second floor of the laboratory, immediately upstream of the turbine test stand (fig. 6). The dynamometer control console, valve control panel, and major items of instrumentation are located in the control room. Signals from pressure transducers, thermocouples, and other sensors are relayed through an input panel near the model turbine to an output panel mounted in the control room. These signals are continuously monitored by a Hewlett Packard HP85 computer and a 3421A Data Acquisition and Control Unit. This system provides the operator with the current operating status of the turbine model. Large viewing windows allow the operator to see most areas of the test facility, and a closed circuit TV monitor in the control room permits viewing of the turbine runner through the plexiglas draft tube.

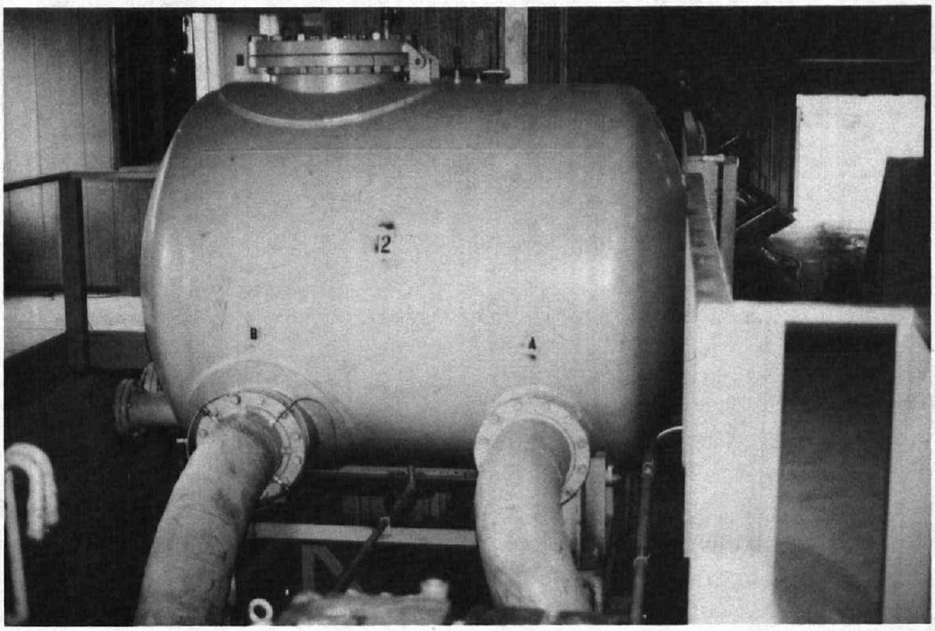


Figure 4. - Head tank for the model turbine. Flow from the Rotovalve enters the head tank on the right and exits through the model penstock on the left. The control room is located through the window on the left.

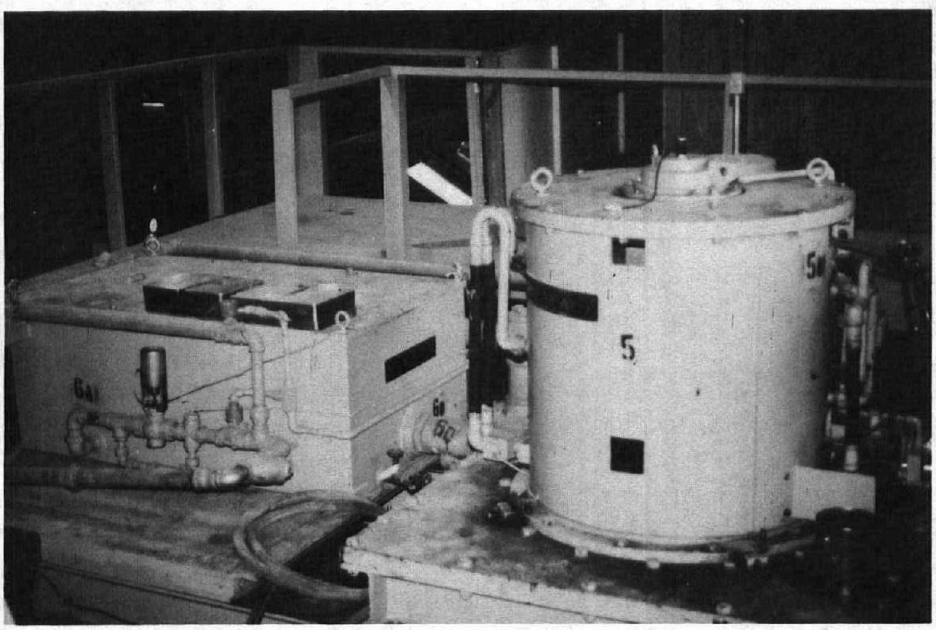



Figure 5. - Dynamometer (right) and the dynamometer cooling water tank installed on top of the test stand frame.

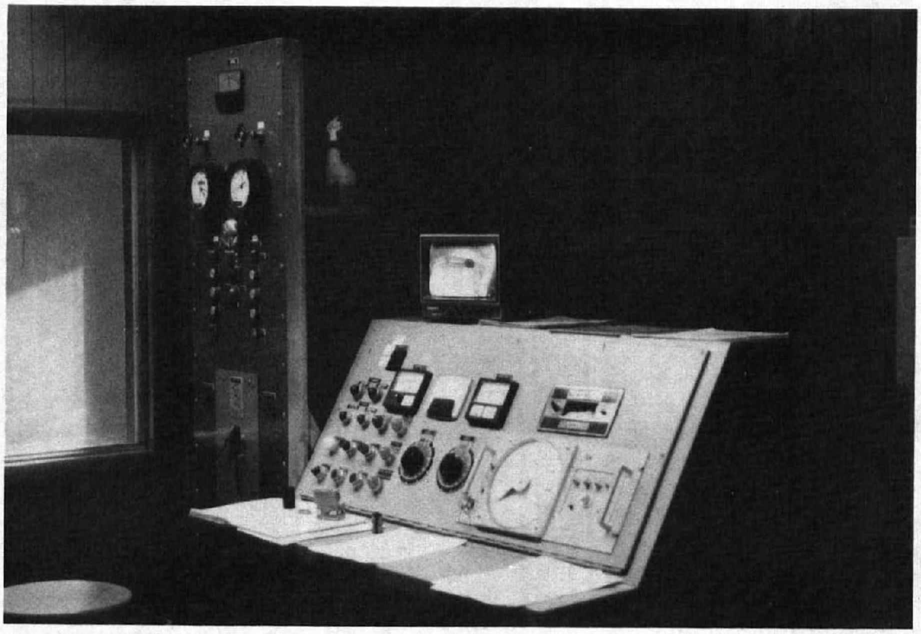


Figure 6. - Test facility control room showing the valve control panel (left) and dynamometer control console (right).

## Cooling Water and Bearing Lubrication

Cooling water for the dynamometer and lubrication water for the carbon sleeve bearing are provided from the left-hand branch of the bifurcation inside the laboratory. This 24-in (61.0-cm) pipeline serves another research effort, but may eventually become the primary emergency bypass for the turbine facility.

A 3-hp air compressor (fig. 7) supplies air to the oil mist lubrication units and the runner reaeration system. No provision has been made at this time for supplying compressed air to the head tank or tailwater tank.

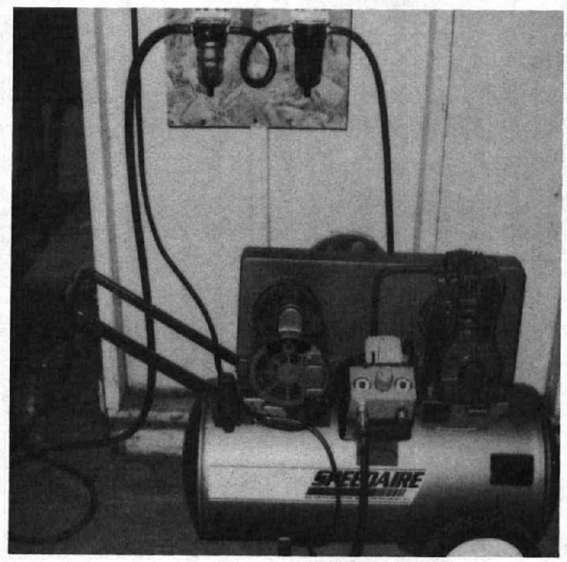


Figure 7. - Three-hp, 20-gal air compressor with oil/water and particulate filters. The compressor supplies air to the oil mist lubrication units.

## Discharge Piping

About 40 ft (12.2 m) of 20-in (50.8-cm) diameter pipe was installed downstream of the tailwater tank to carry the discharge from the tailwater tank to the wasteway. Two 60° bends align the flow for discharge into the wasteway. The 14-in (35.6-cm) diameter standpipe is installed just outside the south wall of the laboratory, approximately 2 ft (0.61 m) upstream of the motor-operated 18-in (45.7-cm) butterfly valve. The standpipe was shortened to eliminate excessive wind loads; it now rises about 25 ft (7.62 m) above the centerline of the tailwater tank, as compared to 42 ft (12.8 m) at Estes Powerplant.

## Electrical

Electrical wiring from the control room to the turbine area was installed in aluminum conduit. The wiring for the 18-in (45.7-cm) butterfly valve, located outside of the building, was installed using flexible, weatherproof conduit. In addition, data signal wiring from the control room to the turbine area was installed in separate conduit to reduce signal interference.

The auxiliary controllers for the 10-in (25.4-cm) cone valve (Rotovalve) and 18-in (45.7-cm) butterfly valve were installed on the supporting structures for the head tank and dynamometer, respectively, where they can be easily reached by personnel in the model turbine area.

The Rotovalve and dynamometer were installed on separate electrical circuits, so that a fault in the dynamometer circuit would not interfere with the emergency closure of the Rotovalve. In the event of a total power failure at the facility, flow through the model turbine must be stopped quickly to prevent turbine runaway. This must be accomplished using the manual bypass and shutoff valves described earlier.

Other options considered for the emergency shutoff system included a UPS (uninterruptable power supply) on the Rotovalve, or a hydraulic actuator to control the manual bypass and shutoff valves. The preferred alternative for a future emergency bypass system is to use the left hand branch of the bifurcation as the emergency bypass. A hydraulic actuator would control the operation of bypass and shutoff valves.

## Oil Misters

Three precision bearings are lubricated by oil mist supplied by three oil mist units. Compressed air was originally supplied to the misters by a 1-1/2-hp air compressor already present in the laboratory. Following initial runs, a buildup of oil shellac within the air regulators on the misters caused the regulators to stick open at the start of each run. It was suspected that the oil supplied with the oil mist units when they arrived from Estes Powerplant had deteriorated due to age, causing the shellac buildup. The air regulators were cleaned, and the oil mist reservoirs were drained, cleaned, and refilled with a new oil recommended by the dynamometer manufacturer. After several hours of operation, the shellac buildup returned. Following the failure of the 1-1/2-hp air compressor, a new 3-hp (2.24-kW), 20-gal (75.7-L) air compressor was purchased. This compressor is equipped with water, oil, and particulate filters, and an automatic condensate blowoff valve. Since the installation of the new compressor, the shellac buildup has ceased and the misters have worked well.

## Bearing Inspection and Replacement

The model turbine and dynamometer as a unit contain six bearings, shown schematically in figure 8. The model turbine bearing is a carbon sleeve, lubricated and cooled by waterflow through the bearing. Immediately above this bearing is the turbine precision bearing that is lubricated by oil mist and supports the bottom of the model turbine shaft. The rotor of the dynamometer rides between two grease lubricated trunnion bearings. Also, an additional pair of precision bearings is mounted between the two trunnion bearings. Following installation of the dynamometer and model turbine into the test stand, the bearing manufacturer recommended that the two trunnion bearings be replaced. When the dynamometer was disassembled (see app. E for details), both top bearings were in excellent condition. The top trunnion bearing was replaced because it was easily accessible. However, the excellent condition of the top bearings, and the difficulty of further disassembly of the dynamometer prompted the decision to reassemble the unit without examining the bottom bearings.

In addition to inspection of the bearings, the turbine shaft was removed from the test stand to permit lubrication of the upper and lower floating couplings. The couplings were completely degreased and then packed with grease before reinstallation.

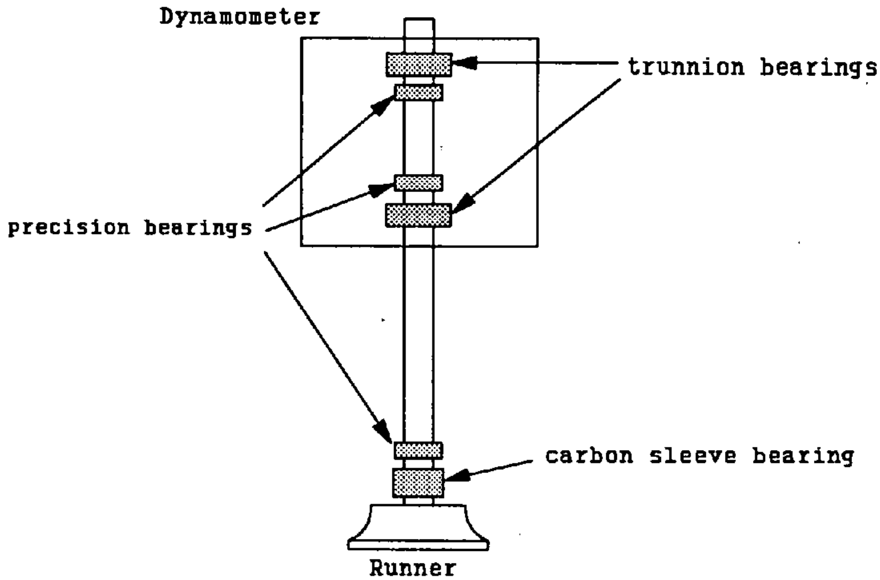



Figure 8. - Location of dynamometer and turbine bearings.

### Wicket Gate Assembly

During the installation of the turbine model into the test stand, the wicket gate handwheel assembly was removed to prevent damage to the handwheel mechanism and the digital counter. After reinstallation, initial tests showed that the wicket gate calibration was no longer consistent with data obtained while the model was at Estes Powerplant. An analysis of the wicket gate setting showed that the gate opening for a given counter reading was 2.2° larger than that indicated by the previous calibration data. Appendix F contains the revised gate calibration.

## CHECKOUT TESTS

Following installation of the facility, a series of checkout tests was performed. The objective of these tests was to ensure the proper operation of cooling and lubrication systems, warning and safety systems, and the dynamometer control systems. A full-load checkout was performed to ensure the safe operation of the model in regions of high load and rough operation.

Initial attempts to operate the model were unsuccessful due to improper setting of a number of pressure switches in the cooling water circuit. Following readjustment of pressure switches, the turbine was operated for the first time at a 14° gate opening for about 1 hour. Problems were noted with the pressure switch monitoring the water supply to the carbon sleeve bearing cooling system during this run. This switch was originally set to operate at 85 lb/in$^2$ when the model was installed at Estes Powerplant. The switch was readjusted to operate at 55 lb/in$^2$ and the flow through the carbon sleeve bearing was monitored. The flow rate was about 2 gal/min with no significant temperature rise.

Following the initial operation at 14° gate opening, a second run was made at 26.25° gate opening. During the run, temperatures of 127 °F were noted on thermocouples 1 and 3, which monitor the dynamometer inductor ring. There was concern because the Load Test Record data sheet stated, "If any temperature exceeds 120 °F, shut down the unit and investigate possible cooling water problem." Also, the DOC (Designer's Operating Criteria) indicated that the cooling system reaches its maximum capacity when the cooling water reaches 130 °F, and a temperature of 165 °F or above will cause the removal of excitation from the dynamometer.

Measurements of stem position on the modulating valve in the cooling water circuit indicated that it might not be operating properly. There was some discussion of the purpose of the unused J-type thermocouple meter (G11) on the dynamometer control console. This gauge was shown on Reclamation Drawing 1222-D-1537, but no electrical connections were indicated.

These events prompted a complete reevaluation of the operation and monitoring of the dynamometer cooling system. The modulating valve was tested and found to be working properly. However, a close examination of the manufacturer's drawings for the dynamometer showed that G11 had originally been intended for monitoring the discharge side of the dynamometer; this temperature, not the temperature of the inductor ring, affects the dynamometer excitation circuit. The DOC gives no guidelines for the temperature of the inductor ring, except that the inductor ring temperature should not tend to increase under constant load.

Following these discoveries, a new J-type thermocouple was installed at the discharge side of the dynamometer, and the data acquisition system was modified to monitor a T-type thermocouple that had been previously installed at this point. In all runs since the installation of these thermocouples, the cooling water temperature has remained at or below 96 °F on the discharge side of the dynamometer. Appendix C provides a complete description of the cooling system operation.

During the last checkout test, the operation of the overspeed circuit was tested and found satisfactory. The overspeed circuit will cause automatic closure of the Rotovalve and shutdown of the facility if the turbine speed exceeds 3,350 r/min.

The turbine was operated at a 21° wicket gate opening over a large speed range to demonstrate negative and positive swirl and the noise associated with the vortex breakdown. The facility seemed to be structurally sound even during operation in very rough zones. Some vibration of the head tank and its supporting structure was noted. This has been monitored during subsequent runs and has not been so severe as to limit operation.

## OPERATION OF THE TEST FACILITY

### Basic Operating Procedures

The basic operating procedures for the test facility are unchanged from those used at Estes Powerplant. The operations checklists used are:

- Filling main laboratory pipeline
- Preoperation inspection
- Setup for operation
- Start operation
- Shutdown procedure

The checklists have all been revised to suit the facility as it is installed at the hydromachinery laboratory. The checklists are included in appendix A.

The operation of the turbine is controlled from the dynamometer control console. Both speed control and load control options are available; speed control is most commonly used. During cavitation testing, the data acquisition system is used to help set the desired test conditions. Visual observations of cavitation on the runner are also made. A short video tape of some cavitation conditions has been prepared. The video also recorded the draft tube vortex, along with its associated noise.

### Improvements

Improvements to the facility include thermocouples to monitor the turbine bearing temperature and dynamometer cooling water discharge temperature. The long distance from the control room to the model turbine has also prompted the installation of a closed circuit television system. This allows the operator to view the runner and draft tube from the control room.

### Emergency Procedures

Emergency procedures for the facility have changed substantially. If a power failure were to occur at the hydromachinery laboratory, flow through the turbine model must be stopped by manually closing the 20-in (50.8-cm) butterfly valve downstream of the bifurcation. A 10-in (25.4-cm) bypass equipped with a manually operated butterfly valve has been installed just upstream of the 20-in (50.8-cm) shutoff valve. Proper operation of these valves during an emergency has been described in a separate document included in appendix B. This document also describes procedures for situations including loss of oil mist lubrication or loss of cooling water supply.

### Operation Limitations

**Head.** - The total available static head from Horsetooth Reservoir is about 250 ft (76.2 m) with the reservoir at maximum normal water surface. Due to irrigation demands on the reservoir this head may often drop significantly. During the summer of 1989, the static head available dropped to less than 200 ft (61.0 m).

**Cavitation coefficient.** - The additional length of the discharge line downstream of the tailwater tank and the presence of the two 60° bends have increased the head loss in this portion of the discharge path; as a result the NPSH (net positive suction head) cannot be set less than about 30 ft (9.14 m). With Horsetooth Reservoir at full capacity, this permits a minimum cavitation coefficient ($\sigma$) of about 0.12. Under the low head conditions experienced during the summer of 1989, the minimum $\sigma$ obtained was 0.155. According to data supplied by Allis Chalmers, this range of $\sigma$ values is on the border of the point of efficiency loss due to cavitation. One attempt was made to run a cavitation break test. The results of this run are shown in figure 9. The data are typical of a cavitation break test; unfortunately, the lowest $\sigma$ was slightly above the point where one expects a dramatic drop in efficiency.

The shortened length of the standpipe noted previously has limited the maximum NPSH available to about 50 ft (15.2 m). Any higher NPSH causes discharge of water through the top of the standpipe, with resulting local erosion near the wasteway. At maximum head this limits the maximum $\sigma$ to about 0.2, but at lower heads, $\sigma$ values of 0.3 to 0.4 can easily be obtained. This is sufficient to eliminate cavitation on the turbine runner under most operating conditions.

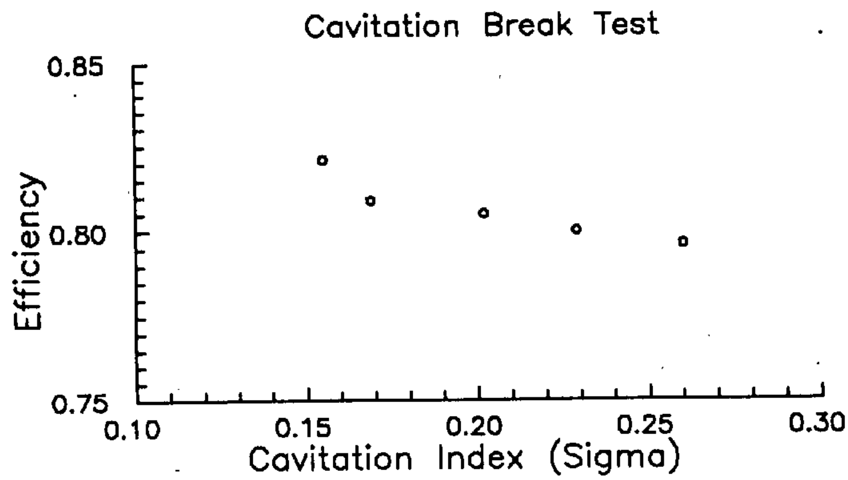



Figure 9. - Results of attempted cavitation break test at 17° gate opening and speed ratio = 0.70.

**Power.** - Initially there was concern that the cooling capacity of the dynamometer cooling water circuit would not permit operation above about 200 hp. However, after reexamining the operation of the cooling system and beginning to monitor the temperature of the discharge water from the dynamometer, brake horsepower outputs of up to 300 hp have been safely reached. At no time has the cooling water temperature on the discharge side of the dynamometer exceeded 96 °F. This is well below the specified operating maximum of 130 °F stated in the DOC.

## Recommended Changes and Improvements

**Air compressor.** - The use of the turbine model for research in which control is needed of the upstream and downstream water surfaces will require the use of a high capacity air compressor.

**Butterfly valve position indicator.** - During checkout tests and later operations, the long distance from the control room to the tailwater tank has caused poor response of the control room tailwater pressure gauge. Because the control room is on the second floor of the laboratory, there is no indication on the gauge until the tailwater head reaches about 12 ft (3.66 m). Possible solutions for these problems include a pressure transducer on the tailwater tank with a meter readout at the control console, a pressure transducer on the 14-in (35.6-cm) standpipe with meter readout at the control console, or an angular position indicator for the butterfly valve. The position indicator would only give the operator a relative feeling for the level of the tailwater but is by far the least expensive alternative.

**Emergency shutdown system.** - The current emergency shutdown procedure requires quick, clear thinking and proper execution by two people to shut down the facility in the event of a power outage. A safe and more effective system would be to use the left hand branch from the bifurcation (24-in pipe) as the emergency bypass and to have its operation controlled by a UPS system or a hydraulic actuator. This would provide immediate, safe shutdown of the facility, with no damage to the turbine model, and no danger to personnel in the laboratory.

## INSTRUMENTATION AND DATA ACQUISITION

### Sensors

**Strobe light.** - The strobe light is part of a B&K (Brüel and Kjær) vibration and rotating machinery equipment package purchased by the project. The unit is equipped with an optical, external trigger, allowing the strobe to be automatically synchronized to the shaft speed of the turbine. Also, internal triggering options permit controlled viewing of each individual bucket on the runner. The strobe is battery operated and can be recharged repeatedly.

**Optical torque sensor.** - Two optical triggers are used as part of the optical torque sensor developed by the project. The triggers sense the passage of the leading edge of a reflective tape strip attached to the model turbine shaft. The two triggers and corresponding tape strips are placed at different positions along the length of the shaft. An oscilloscope is used to measure the elapsed time between the passage of the two tape strips. As torque on the shaft increases, the shaft twists, and the oscilloscope senses this as a time shift between the two pulses.

**Accelerometers.** - Two accelerometers are used on the project. The first is a small portable unit, which was also part of the B&K vibration package. The second accelerometer is on loan from Reclamation and is a B&K Type 4370. Stud mounts for this sensor have been installed on the T-beams surrounding the model turbine.

**Pressure transducers.** - Two types of pressure transducers are used. Two Endevco piezoresistive, absolute pressure transducers are used for cavitation detection and are usually mounted at the draft tube throat. The second set of transducers are Pace differential pressure transducers. These transducers are permanently installed for measuring the pressure differential across the venturi, the pressure on the upstream side of the model turbine, and the pressure on the downstream side of the model turbine. The HP85 computer processes the signals from these transducers and calculates the operating conditions for the turbine.

**Thermocouples.** - T-type thermocouples monitor the temperature of the turbine bearings, incoming water, and the cooling water discharged from the dynamometer. These thermocouples are all monitored by the HP85 computer. In addition, a new J-type thermocouple has been installed to monitor the dynamometer cooling water discharge temperature on meter G11 at the dynamometer control console.

**Hydrophone.** - A B&K Type 8103 hydrophone is used for cavitation detection. The hydrophone is mounted through the top viewing window of the tailwater tank, and hangs in the quiet flow just above the draft tube exit. The signals from the hydrophone and accelerometer are both relayed through a B&K Type 2635 charge amplifier.

**Acoustic emission.** - A Physical Acoustics Corporation 3000/SPARTAN AE system is on loan from Reclamation. AE transducers detect the high-frequency acoustic energy released by the development of cracks in a solid material. AE transducers are also sensitive to the high frequency noise created by the implosion of cavitation bubbles. Thus, AE offers two prospective means of detecting cavitation. Cavitation bubbles imploding in the flow may be detected by sensors mounted on the flow boundaries, or cavitation that causes damage to a flow boundary will create true AE signals that may be detected by a sensor in contact with the damaged material.

**Magnetostriction.** - A prototype magnetostriction actuator was purchased from Edge Technologies, Ames, IA. The unit uses the magnetostrictive material ETREMA Terfenol-D. This material can be strained by applying a magnetic field. Conversely, this material produces a magnetic field when it is strained. This unit is planned for installation in the vacuum chamber at Reclamation's Hydraulic Laboratory in Denver for cavitation experiments. Also, several small strips of Terfenol-D material have been obtained for testing with the model turbine. The strips may be attached to the turbine shaft using an epoxy glue. An inductive pickup loop surrounding the shaft will detect changes in the magnetic field caused by stressing of the Terfenol-D.

### Oscilloscope

The Hewlett Packard 54501A digitizing oscilloscope is used for recording time domain signals from the accelerometer, hydrophone, and pressure transducers. The oscilloscope has also been used in the development of the optical torque sensor described previously.

### Dynamic Signal Analyzer

The Hewlett Packard 3561A dynamic signal analyzer is used for performing narrow band and one-third octave analyses of output signals from the accelerometer, hydrophone, and pressure transducers.

### Data Acquisition System

The data acquisition system consists of a Hewlett Packard HP85 computer and a 3421A Data Acquisition and Control unit. A computer program written in BASIC on the HP85 drives the system.

The computer program performs three main functions. The first is to scan each pressure transducer, the thermocouples, the torque load cell, and the tachometer generator. The program computes the basic parameters describing the operation of the turbine. The second function is to aid the operator in establishing appropriate test conditions for cavitation experiments. The data required to compute $\sigma$ are taken, and when the required $\sigma$ value is reached, an alarm is sounded. The last function of the program is to monitor a single transducer. This is useful in debugging problems with individual transducers. The program output can be routed either to the screen or to a thermal printer. A flowchart for the program has been included in appendix G.

## TECHNIQUES FOR CAVITATION DETECTION

The second objective of the project was to evaluate four techniques for determining the presence of cavitation on the runner of the model turbine. Narrow band and one-third octave analyses of hydrophone and accelerometer output have been tried earlier on some hydropower units of the C-BT (Colorado-Big Thompson) Project (Skinner, 1986, 1987). AE measurements involving cavitation have been performed satisfactorily in the Reclamation Hydraulic Laboratory, Denver, CO, by Mefford (1988). Recent developments in new magnetostrictive materials show promise as supersensitive detectors for measuring stress waves in the shaft of a turbine (Hernando, Vazquez, and Barandiaran, 1988). Shaft torsional oscillations recorded at Flatiron Powerplant and Grand Coulee Third Powerplant were excited by hydraulic disturbances on the runner (Eilts and Campbell, 1979). Magnetostrictive materials have also been applied in recently patented torque sensors (Eaton Corporation, Milwaukee, WI).

### Sensor Placement

The B&K Type 8103 hydrophone was installed in the tailwater tank. The hydrophone was suspended through the top viewing port, about 6 in (15.2 cm) below the free water surface. This placement left the hydrophone above the high velocity flow emerging from the draft tube. This is comparable to the location used for tailrace measurements at Flatiron and other C-BT powerplant sites. The B&K Type 4370 accelerometer was stud-mounted to the turbine test stand frame (fig. 10). This location is in direct structural contact with the spiral case, stay ring, and distributor assemblies. An Endevco Model 8530-100 piezoresistive absolute pressure transducer was flush-mounted at the draft tube throat, directly below the runner (fig. 11).

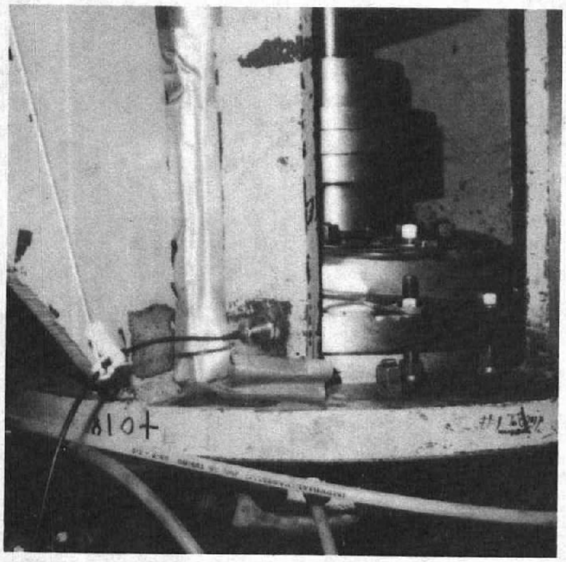


Figure 10. - Accelerometer, stud-mounted on the turbine test stand.

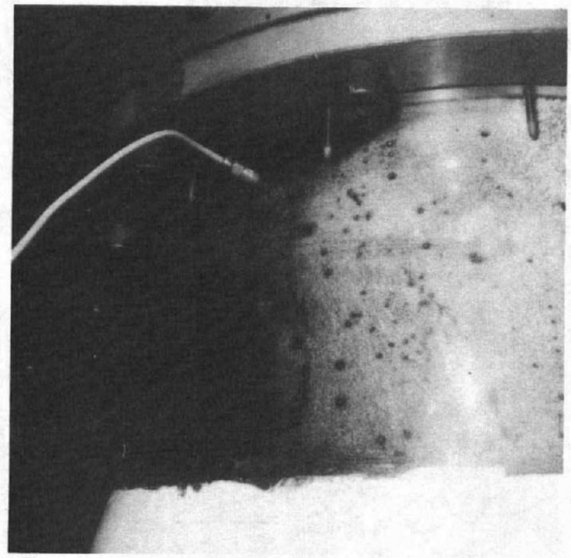


Figure 11. - Piezometric pressure transducer flush-mounted at the draft tube throat.

## Narrow Band and One-Third Octave Output

Runs for all three sensors were performed at full gate opening in regions near zero swirl to eliminate interference from draft tube surging. The desired cavitation point was achieved by varying the tailwater level while maintaining a fairly constant speed ratio, ($\phi$), at a given wicket gate opening. The speed ratio $\phi$ is defined by:

$$\phi = \frac{\pi N D_2}{60\sqrt{2gH}}$$

where:

| | | |
|---|---|---|
| N | = | shaft speed (r/m) |
| $D_2$ | = | runner throat diameter (ft) |
| H | = | net head (ft) |
| g | = | acceleration of gravity (ft/s$^2$) |

Although changes in the tailwater level cause changes in the net head, a constant speed ratio could be maintained by varying the shaft speed of the model. This was easily accomplished using the speed control capabilities of the dynamometer.

Based on the first author's experience at the Flatiron units, one-third octave and narrow band analyses were performed on hydrophone, accelerometer, and pressure transducer output (Skinner, 1986; 1987). The overall, one-third octave rms levels for the hydrophone, pressure transducer, and accelerometer are plotted against the cavitation coefficient, $\sigma$, in figures 12, 13, and 14. A pronounced increase in rms level corresponded to the onset of cavitation, which was visually evaluated to be about $\sigma = 0.25$ for operation at full gate.

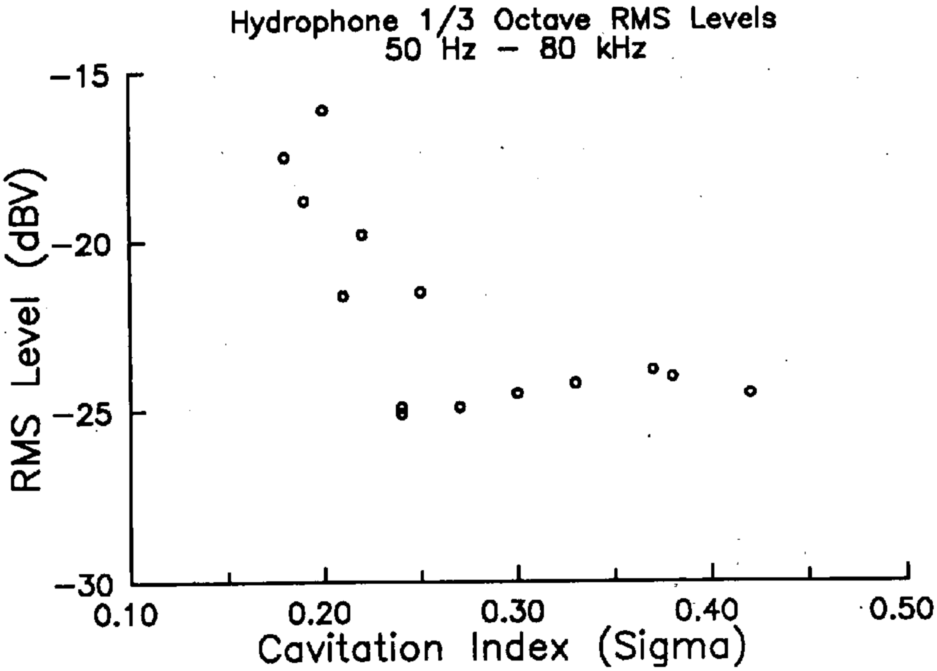



Figure 12. - Hydrophone one-third octave rms levels vs. σ. These data were collected at full gate opening and a speed ratio of 1.02.

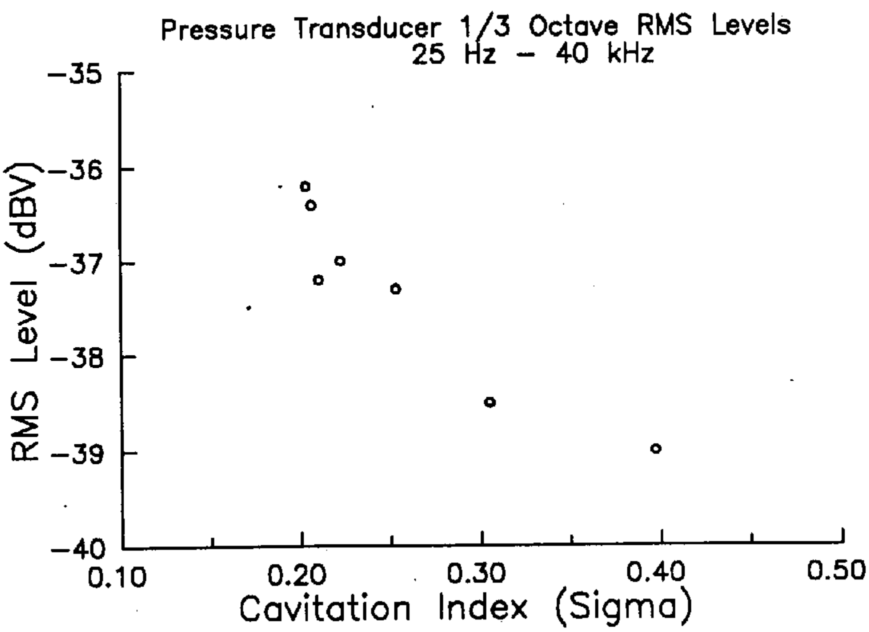



Figure 13. - Pressure transducer one-third octave rms levels vs. σ. These data were collected at full gate opening and a speed ratio of 1.03.

In addition to the variation in rms levels, one-third octave and narrow band analyses of the hydrophone output showed a definite drop in the signal level above about 5 kHz as cavitation activity increased. Figures 15 and 16 show examples.

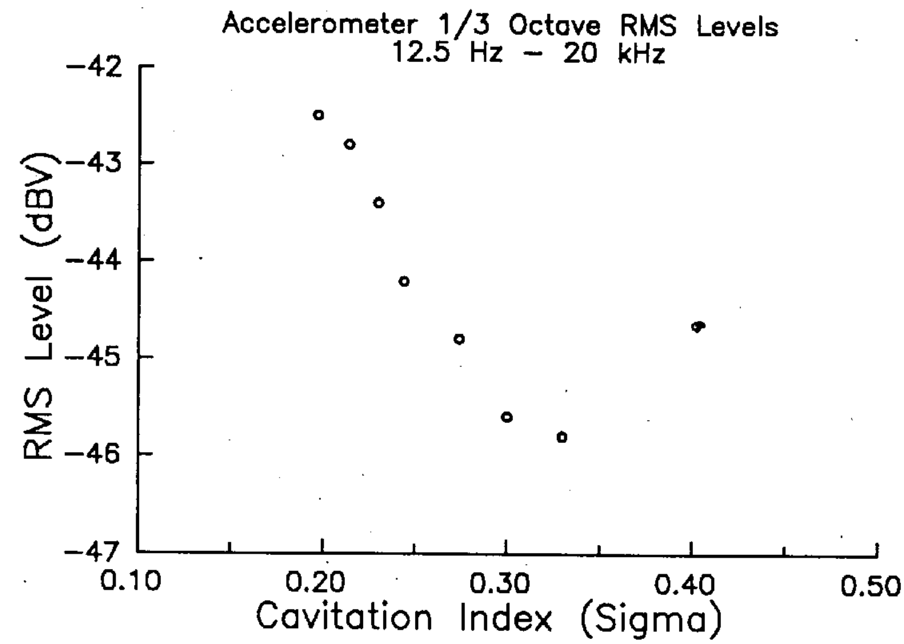



Figure 14. - Accelerometer one-third octave rms levels vs. σ. These data were collected at full gate opening with the speed ratio held constant at 1.03.

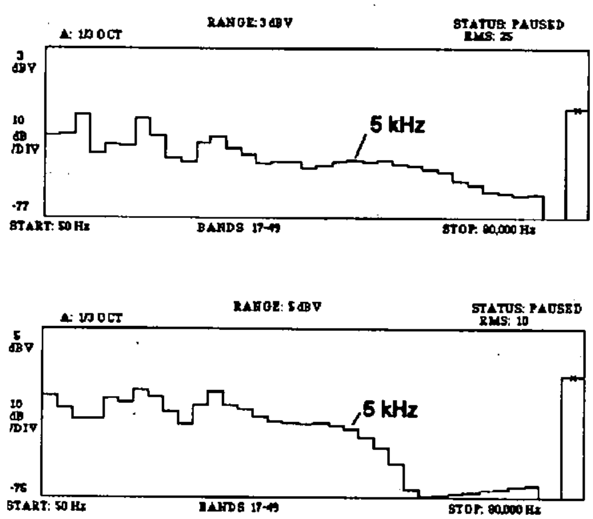



Figure 15. - Hydrophone one-third octave analyses. The top plot is at σ = 0.27, while the lower plot is at σ = 0.18. As cavitation activity increases, components above about 5 kHz drop out.

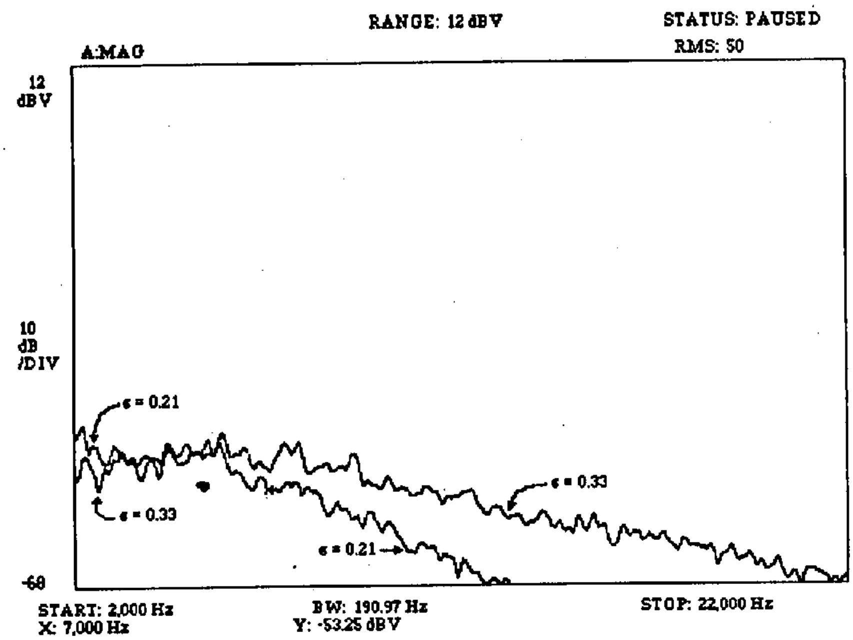



Figure 16. - Hydrophone narrow band analyses. Note the loss of high frequency signal as cavitation activity increases.

Narrow band analyses of the pressure transducer output also gave some indication of cavitation. Under noncavitating conditions, the blade passing frequency dominated the signal. However, as the tailwater level was lowered and cavitation increased, the blade passing frequency became less dominant. This behavior is shown in figures 17 and 18. Note that the blade passing frequency itself is different in the two figures because the shaft speed was varied to maintain the same speed ratio and unit power as the tailwater level was changed.

## Time Domain Output

The Endevco pressure transducer mounted just below the runner in the draft tube wall gave an indication of cavitation activity when the signal was monitored in the time domain. Figure 19 shows a trace that was obtained at $\sigma$ = 0.25; some bursts of cavitation were visible on or near the trailing edges of the buckets.

The accelerometer also provided some indication of cavitation when signals were monitored in the time domain. During runs at cavitating conditions, time traces recorded with the digitizing oscilloscope indicated very high frequency signals, between 350 to 500 kHz. Figure 20 shows one such trace. These short-duration, high-frequency signals are far beyond the range of the accelerometer, which has a resonant frequency of about 25 kHz. Although the amplitude of these signals is unreliable, their presence during cavitating conditions indicates that high-frequency sensors such as AE transducers may be useful for cavitation detection.

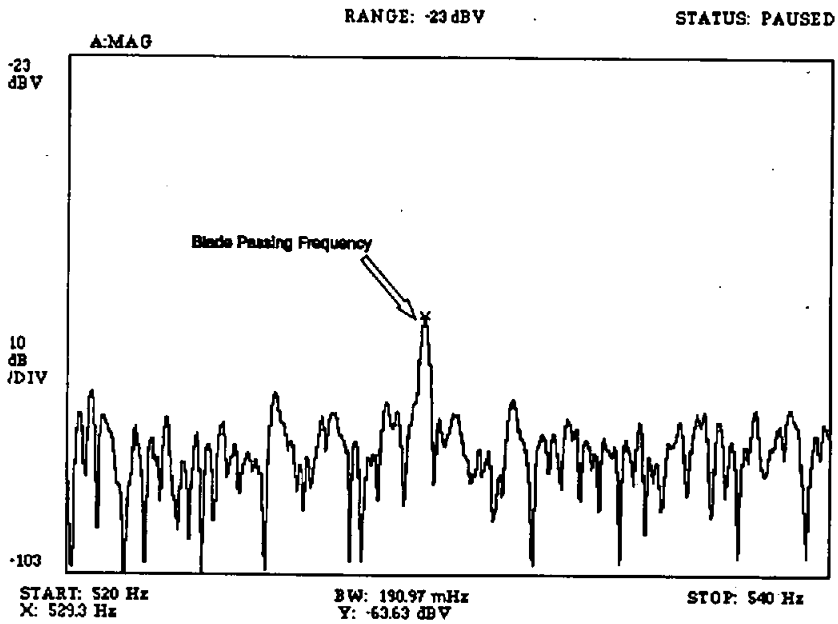



Figure 17. - Pressure transducer narrow band analysis with no cavitation. Note the strong signal at the blade passing frequency (approx. 530 Hz).

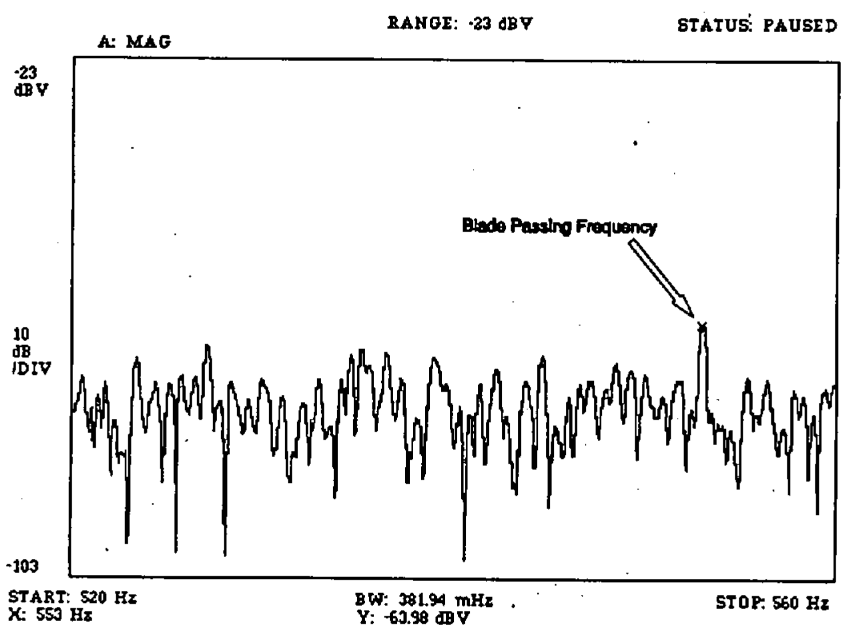



Figure 18. - Pressure transducer narrow band analysis with cavitation. The blade passing frequency (approx. 554 Hz) becomes less dominant as cavitation intensity increases.

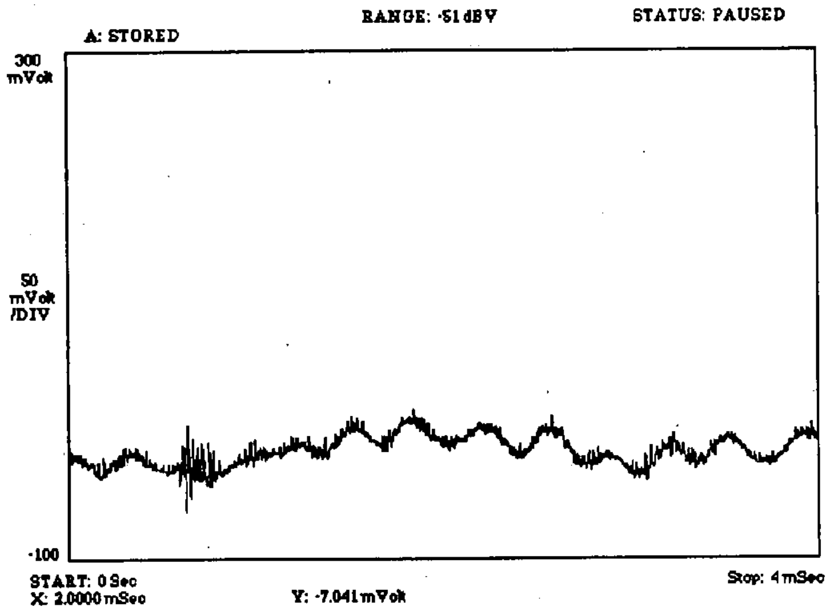



Figure 19. - Time domain output from pressure transducer. Note the burst signal at the lower left. The frequency of this burst is about 36 kHz.

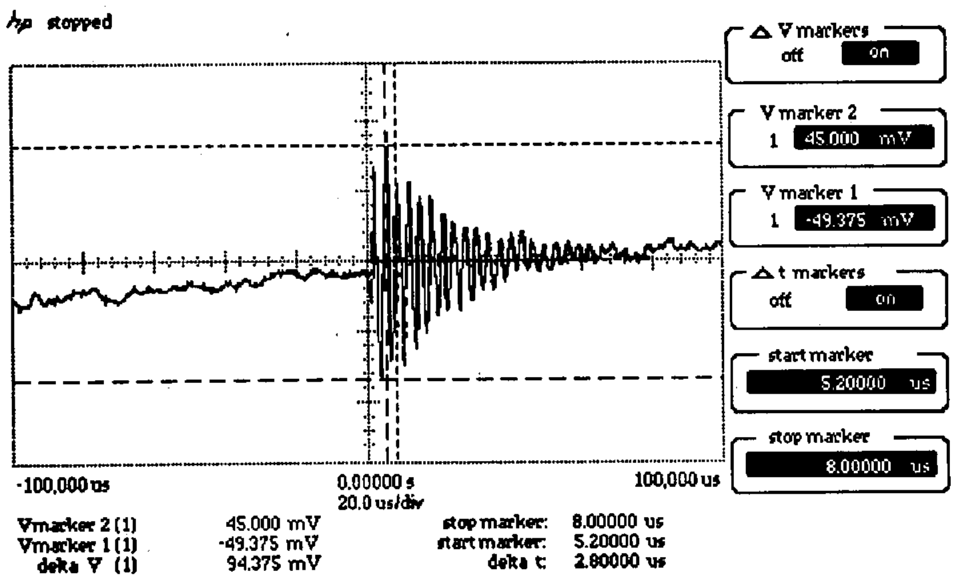



Figure 20. - Time domain output from accelerometer. Note the extremely high frequency of 357 kHz.

## AE (Acoustic Emission) Testing

AE measurements were made using a Physical Acoustics Corporation 3000/SPARTAN AE system. Establishing a threshold level of AE activity between cavitating and noncavitating conditions was not attained in the limited investigation.

Testing was done using a calibrated AE signal generator to try to determine portions of the turbine structure that would be sensitive to cavitation occurring on the runner. The draft tube was removed and an AE transducer configured as an exciter was placed on the runner (fig. 21). An AE sensor was then located at various points around the structure and output signal levels were recorded. The best coupling with the least interference from random excitation impacts of a small hammer on other parts of the turbine assembly was found between the runner and the shaft just below the lower coupling flange (fig. 22). Other locations that were sensitive to signals originating on the runner were the head cover/stay vane ring and the uppermost bearing cap. The bearing cap seemed to be well isolated from signals originating on other portions of the model and test stand structure. Although the shaft was sensitive at the bottom side of the coupling, no signal could be detected above the coupling. Table 2 summarizes the results of the measurements.

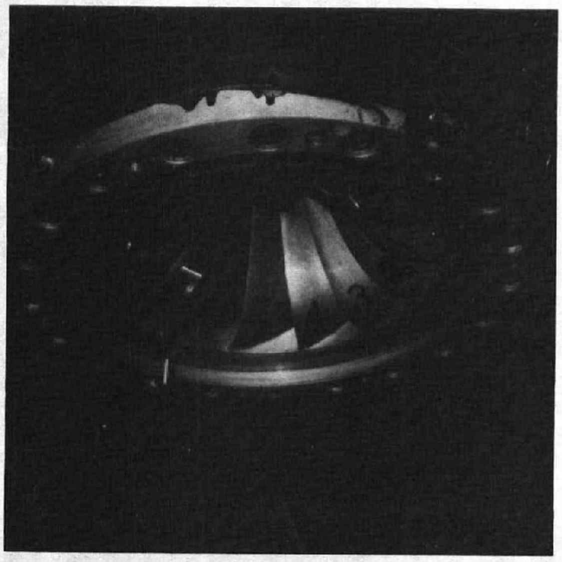


Figure 21. - AE transducer configured as a sending unit mounted on the turbine runner.

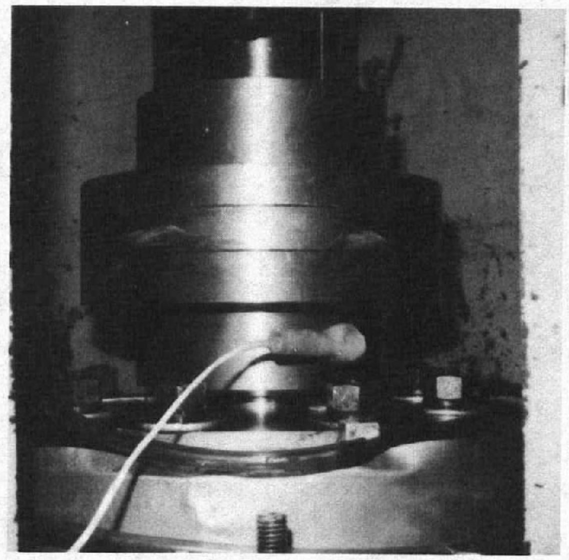


Figure 22. - AE transducer mounted on the lower shaft coupling just above the turbine runner. This transducer was used to receive signals transmitted through the transducer in figure 21.

## Magnetostriction

The magnetostriction phenomenon refers to the strain changes that occur in a material in the presence of an imposed magnetic field. Conversely, magnetostrictive materials also experience changes in magnetization when placed under mechanical stress. James Joule first discovered the magnetostrictive effect in nickel in 1840. Subsequently, it has been shown that all ferrous metals are magnetostrictive. However, maximum strains in these materials are relatively small; the strains in nickel are limited to about 50 parts per million.

The greatest advantage of magnetostrictive materials for sensing applications is that the output is in the form of a changing magnetic field. Changes in the magnetic field are detected by an inductive loop; physical contact with the magnetostrictive material is not required. This eliminates the need for slip rings or telemetry systems.

ETREMA Terfenol-D is a magnetostrictive composite containing the elements iron, terbium, and dysprosium. Strains attainable in Terfenol-D at room temperature approach 2,000 parts per million. This material is currently available in several shapes, including rods and plates. The sensitivity of Terfenol-D is greatly increased when the material is under a compressive prestress. The output is linear, provided some magnetic bias is applied to the material, usually by a permanent magnet or d-c electromagnet.

**Table 2. - Results of AE signal transfer tests**

*AECAL-2 Settings*

AE mode
Amplitude Hi
Exciter located on blade 7
Single-ended transducers
SPARTAN threshold = 80 dB <Fixed>
SPARTAN gain = 0 dB
RTTO/SCETO/RTO are trigger parameters

Burst = 05 µs
Delay = 10 µs
Rise time = 10 µs
Decay = 500
Carrier = 150 kHz
Preamplifier gain = 40 dB

| Receiver location | Input amplitude (dB) | RTTO/SCETO/RTO (µs) | Output amplitude (dB) |
|---|---|---|---|
| Runner | 83 | 20/50/50 | 55 |
| Shaft - bottom of coupling | 83 | 20/50/50 | 34 |
| Bearing cap | 93 | 20/50/50 | 38 |
| Stay vane support ring (headcover) | 83 | 20/50/50 | 40 |
| Shaft - bottom of coupling | 93 | 20/50/50 | 39 |
| Shaft - top of coupling | 99 | 20/50/50 | No signal |
| Shaft - above coupling | 99 | 20/50/50 | No signal |
| Stay vane support ring | 83 | 500/1000/4000 | 49 |
| Stay vane support ring while turning shaft by hand | 83 | 500/1000/4000 | 35 to 55 |
| Draft tube throat ring | 83 | 500/1000/4000 | 44 |
| Shaft - bottom of coupling | 93 | 500/1000/4000 | 38 |
| Uppermost bearing cap | 93 | 500/1000/4000 | 36 |

Note: The uppermost bearing cap seemed to be well isolated from noise originating from the penstock, spiral case, and other portions of the structure. Most other locations were sensitive to such extraneous noise.

For sensing applications on the shaft of a turbine, amorphous metallic glasses in film or filament shape with circular cross section may prove more effective. Eaton Corporation, Milwaukee, WI, holds several patents on the use of metallic glasses for torque measurement.

Initial experience with magnetostrictive materials was gained in tests conducted with a magnetostrictive actuator incorporating a Terfenol-D rod. A schematic diagram of the actuator appears in figure 23. The actuator is made up of the Terfenol-D rod, surrounded by a coil for excitation or output, a permanent magnet to apply the magnetic bias, and a prestressing assembly.

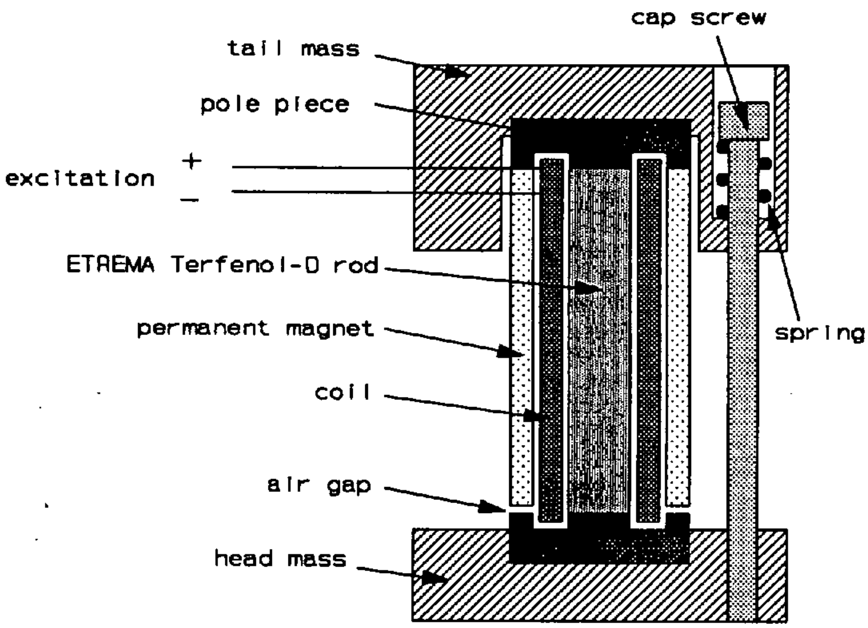



Figure 23. - Schematic diagram of magnetostrictive actuator. The actuator utilizes the magnetostrictive material ETREMA Terfenol-D.

To test the sensitivity of the actuator a "pencil test" was performed. The pencil test is a qualitative test commonly used in the AE field for testing of very sensitive transducers. A medium hardness (HB), 0.5-mm-diameter pencil lead was extended about 0.25 in (6.4 mm) out of the pencil and placed in contact with the surface of the actuator at a 75° angle. A force was then applied perpendicular to the axis of the pencil lead, causing the lead to break. Care was taken so that the pencil did not strike the actuator after the lead broke. An oscilloscope trace of the resulting output for the actuator is shown in figure 24.

## Torque

Torque and torque variation measurements were obtained using a combination of two optical triggers and a digitizing oscilloscope. The basic concept of the sensor has been described previously. Utilizing the basic equation

$$\theta = \frac{TL}{JG}$$

the torque can be expressed as a function of the time shift between the passage of an upper and lower marker on the shaft, $\Delta t$, and the shaft speed, N, as below.

$$T = C_1 (N) (\Delta t) + C_2$$

The value of the constant $C_1$ is a function of material properties and dimensions of the shaft. The second constant, $C_2$, is also a function of material properties and dimensions of the shaft, and also accounts for any initial misalignment of the markers. A prototype electronic circuit has been developed to analyze the signals from the two optical sensors. This device gives an analog output of Δt. This information alone is not sufficient to compute torque. However, at constant speed, the torque is directly proportional to Δt. Thus, at constant speed, any variation in Δt can be taken as an indication of a variation of torque.

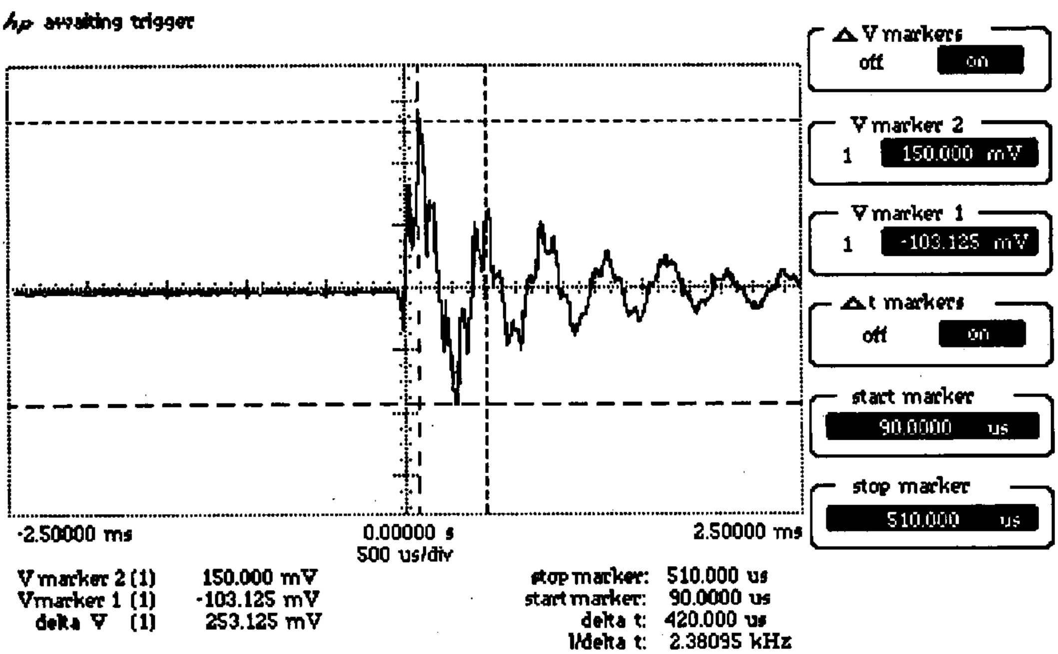



Figure 24. - Pencil test output from magnetostrictive actuator.

Figure 25 shows the signals generated by the two optical triggers and the elapsed time Δt displayed on the oscilloscope. Figure 26 shows a narrow band analysis of the analog Δt output. The shaft does appear to oscillate in an angular vibration mode. Two dominant oscillations at 12.5 Hz and 31.75 Hz appear. Thus far in this research, use of this sensor for cavitation detection has been unsuccessful.

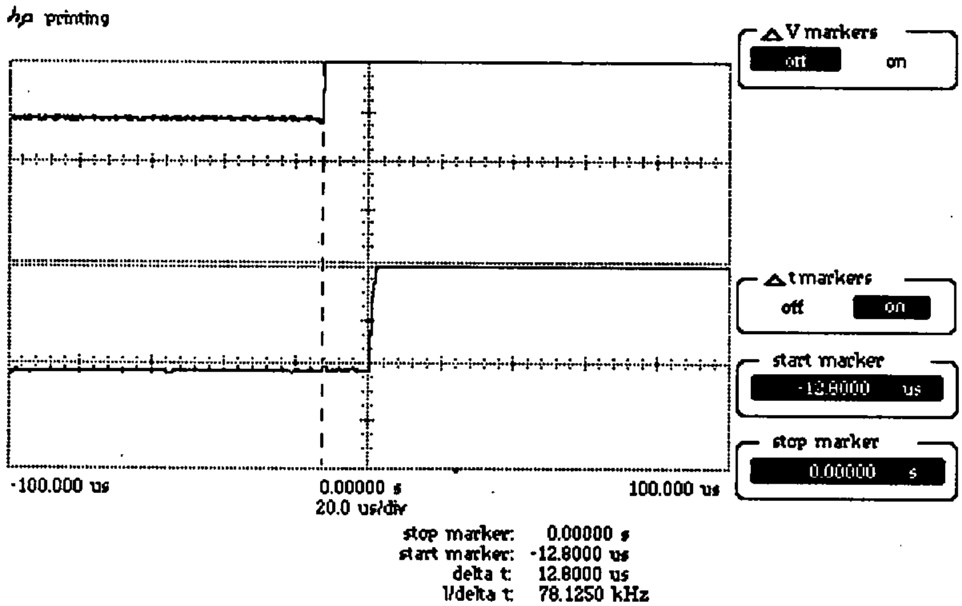



Figure 25. - Torque sensor time shift displayed on the oscilloscope.

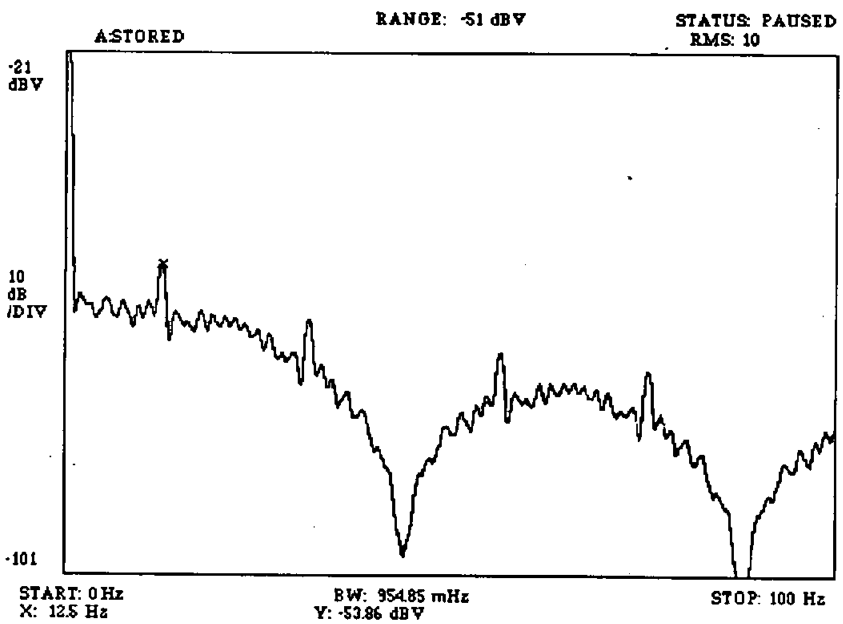



Figure 26. - Narrow band analysis of analog Δt output from the torque sensor.

## BIBLIOGRAPHY


Abbot, P., *Acoustic and Vibration Techniques for Cavitation Monitoring*, Report No. EPRI AP-5385, Electric Power Research Institute, September 1987.

Allen, J. W., W. F. Hartman, and J. C. Robinson, *Acoustic Monitoring of Power Plant Valves*, Report No. EPRI NP-2444-SY, Electric Power Research Institute, June 1982.

Allen, C. M., and L. J. Hooper, "Piezometer Investigation," *Transactions of the American Society of Mechanical Engineers*, No. HYD-54-1.

Aoki, H., J. Maruyama, M. Shimada, K. Tanizaki, S. Yahagi, and T. Saito, "Torque Sensor with Shape Anisotropy," Technical Digest of the 7th Sensor Symposium, pp. 83-86, 1988.

Baladi, J. Y., and C. P. Nyilas, "The Development of a Cavitation Free Sodium Pump for the Breeder Reactor," ASME Winter Annual Meeting, Anaheim, CA, December 1986.

Bark, G., "Prediction of Propeller Cavitation Noise from Model Tests and Its Comparison with Full Scale Data," *Transactions of the ASME, Journal of Fluids Engineering*, pp. 112-120, March 1985.

Beyer, J. R., "The Use of Acoustic Emission to Detect Cavitation in Model and Prototype Applications," Voith Hydro, Inc., 1986.

Beyer, J. R., and T. G. Smith, "Acoustic Emission Characteristics of a Model Francis Turbine Under Cavitating and Non-Cavitating Conditions," Allis Chalmers Fluid Products Company, ASME Winter Annual Meeting, Phoenix, AZ, 1982.

Blake, W. K., *Mechanics of Flow-Induced Sound and Vibration*, vol. I, General Concepts and Elementary Sources, Academic Press, Inc., New York, NY, 1986.

Blake, W. K., *Mechanics of Flow-Induced Sound and Vibration*, vol. II, Complex Flow-Structure Interactions, Academic Press, Inc., New York, NY, 1986.

Brunet, M., and A. Desprets, "Acoustic Detection of a Cavitation Noise in the French Breeder Reactor Phenix," Proceedings, CEA Centre d'Etudes Nucleaires de Cadarache, Specialists Meeting on Boiling Noise Detection, Saint-Paul-les-Durance, France, June 1981.

Burke, H. E., *Handbook of Magnetic Phenomena*, Van Nostrand Reinhold Co., New York, NY, 1986.

Cha, Y. S., "Acoustic Detection of Cavitation in a Prototype Centrifugal Pump," Proceedings, International Symposium on Propellers and Cavitation, Wuxi, Jiangsu, China, April 1985.

Courbiere, P., "An Acoustic Method for Characterizing the Onset of Cavitation in Nozzles and Pumps," Proceedings, ASME Symposium on Flow Induced Vibration, New Orleans, LA, December 1981.

Courbiere, P., J. Defaucheux, and P. Garnaud, "Acoustic Methods in Sodium Flow for Characterising Pump Cavitation and Noise Erosion Correlations," Proceedings, ASME International Symposium on Cavitation Noise, Phoenix, AZ, November 1982.

Dawson, D. G., and M. J. Beesley, "Detection and Location of Pump Cavitation Noise by Acoustic Impulse Analysis," Proceedings, Institute of Acoustics Meeting on Acoustics for Pumps, April 1978.

De, M. K., and F. G. Hammitt, "New Method for Monitoring and Correlating Cavitation Noise to Erosion Capability," *Transactions of the ASME, Journal of Fluids Engineering*, vol. 104, No. 4, December 1982.

Deeprose, W. M., N. W. King, P. J. McNulty, and I. S. Pearsall, "Cavitation Noise, Flow Noise and Erosion," National Engineering Laboratory, Department of Industry, East Kilbride, Glasgow, 1974.

Doige, A. G., and H. S. Alves, "Source Identification Testing for Flow-Generated Noise," Noise-Con 85, Columbus, OH, June 3-5, 1985.

Dowdican, M., G. Silva, and R. L. Lowery, "Detection of Damage in Hydraulic Components by Acoustic Emission Techniques," Oklahoma State University, Fluid Power Research Center, April 1984.

Eilts, L. E., and E. Campbell, *Shaft Torsional Oscillations of Hydrogenerators*, Report No. REC-ERC-79-6, U.S. Bureau of Reclamation, August 1979.

Eller, A., and H. G. Flynn, "Generation of Subharmonics of Order One-Half by Bubbles in a Sound Field," *The Journal of the Acoustical Society of America*, vol. 46, No. 3, pp. 722-727, 1969.

Falvey, H. T., *Draft Tube Surges - A Review of Present Knowledge and an Annotated Bibliography*, Report No. REC-ERC-71-42, U.S. Bureau of Reclamation, Denver, CO, December 1971.

Franklin, R. E., and J. McMillan, "Noise Generation in Cavitating Flows, the Submerged Jet," *Transactions of the ASME, Journal of Fluids Engineering*, pp. 336-341, September 1984.

Graham, L. J., R. L. Randall, and C. Hong, *Acoustic Emission Monitoring of Steam Turbines*, Report No. EPRI CS-2367, Electric Power Research Institute, April 1982.

Harris, C. M., *Shock and Vibration Handbook*, 3rd ed., McGraw-Hill Book Co., Inc., New York, NY, 1988.

Harrison, M., "An Experimental Study of Single Bubble Cavitation Noise," *The Journal of the Acoustical Society of America*, vol. 24, No. 6, pp. 776-782, November 1952.

Hernando, A., M. Vazquez, and J. M. Barandiaran, "Metallic Glasses and Sensing Applications," *Journal of Physics E: Scientific Instruments*, December 1988.

Holl, J. W., and G. F. Wislicenus, "Scale Effects on Cavitation," *Transactions of the ASME, Journal of Basic Engineering*, pp. 385-394, September 1961.

Jorgensen, D. W., "Noise from Cavitating Submerged Water Jets," *The Journal of the Acoustical Society of America*, vol. 33, No. 10, pp. 1334-1338, October 1961.

Khan, M. N., "Preventing Cavitation in Francis Runners," *Water Power and Dam Construction*, August 1987.

Leducq, D., G. Marquette, and C. Fumoux, "Fluid Borne Noise Generation and Transmission in Hydraulic Piping Systems," Inter-Noise 86, Cambridge, MA, July 21-23, 1986.

Liu, S., "Chlorine-Release Test for Cavitation-Activity Measurements," *The Journal of the Acoustical Society of America*, pp. 817-823, 1965.

Macleod, I. D., B. S. Gray, and C. G. Taylor, "The Acoustic Detection of Cavitation in Pumps," Proceedings, Institute of Acoustics Meeting on Acoustics for Pumps, April 1978.

Martin, C. S., "Scaling of Cavitation Noise in Valves," Second Edinburgh Conference on Cavitation, 1983.

Martin, C. S., and P. V. Rao, "Application of Signal Analysis to Cavitation," *Transactions of the ASME, Journal of Fluids Engineering*, pp. 342-346, September 1984.

McNulty, P. J., and I. S. Pearsall, "Cavitation Inception in Pumps," *Transactions of the ASME, Journal of Fluids Engineering*, pp. 99-104, March 1982.

Mefford, B. W., *Experimental Investigations of Cavitation Using Acoustic Emission Transducers*, Report No. PAP-522, U.S. Bureau of Reclamation, Engineering and Research Center, Hydraulics Branch, Denver, CO, 1988.

Mellen, R. H., "Ultrasonic Spectrum of Cavitation Noise in Water," *The Journal of the Acoustical Society of America*, vol. 26, No. 3, pp. 356-360, May 1954.

Milano, B., and W. H. Duncan, *Startup Characteristics of Pump-Generator Unit at Flatiron Powerplant*, Report No. GR-85-5, U.S. Bureau of Reclamation, October 1984.

Miller, R. W., *Flow Measurement Engineering Handbook*, McGraw Hill Book Co., Inc., New York, NY, 1983.

Palde, U. J., *Influence of Draft Tube Shape on Surging Characteristics of Reaction Turbines*, Report No. REC-ERC-72-24, U.S. Bureau of Reclamation, Denver, CO, July 1972.

Prestero, M. G., "A Comparison of Acoustic and Visual Determination of Cavitation Inception on a Model Propeller," thesis presented to the Massachusetts Institute of Technology in June 1979, in partial fulfillment of the requirements for the degree of Master of Science.

Proceedings, Second International Conference on Giant Magnetostrictive and Amorphous Alloys for Sensors and Actuators, Marbella, Spain, October 12-14, 1988.

Rahmeyer, W. J., "Cavitation Noise from Butterfly Valves," *Nuclear Engineering and Design, 1982.*

Scruby, C. B., "An Introduction to Acoustic Emission," *Journal of Physics E: Scientific Instruments*, vol. 20, No. 8, pp. 946-953, August 1987.

Sherman, C. H., "Effect of the Nearfield on the Cavitation Limit of Transducers," *The Journal of the Acoustical Society of America*, vol. 35, No. 9, pp. 1409-1412, September 1963.

Skinner, M. M., "Sound and Vibration Measurements at Flatiron Power and Pumping Plant," U.S. Bureau of Reclamation, Hydraulics Branch, Denver, CO, Phase I, September 30, 1986; and Phase II, September 30, 1987.

Suslick, K. S., "The Chemical Effects of Ultrasound," *Scientific American*, February 1989.

Tourret, J., A. Badie-Cassagnet, G. Bernard, J. P. Foucault, and J. Kermarec, "Experimental Studies of Noise Emission and Noise Generation from a Centrifugal Pump," Proceedings, ASME Winter Annual Meeting, Miami Beach, FL, November 1985.

Urich, R. J., *Principles of Underwater Sound*, 3rd ed., McGraw-Hill Book Co., Inc., New York, NY, 1983.

# APPENDIX A

## Operations Checklists

**GRAND COULEE THIRD POWERPLANT - TURBINE MODEL TEST FACILITY**
**COLORADO STATE UNIVERSITY - FORT COLLINS, COLORADO**
**ENGINEERING RESEARCH CENTER - HYDROMACHINERY LABORATORY**

Last Revision: September 18, 1989 by T. L. Wahl

## FILLING MAIN LABORATORY PIPELINE

| Step | Item | Number | Condition | Checked? |
|---|---|---|---|---|
| 1 | Check Rotovalve RV closed | V35 | Closed | |
| 2 | 2" cooling water supply valve closed | V1 | Closed | |
| 3 | Turbine bearing cooling water valve closed | V6b | Closed | |
| 4 | 24" butterfly valve and 8" bypass valve on Dr. Sandborn's line | | Closed | |
| 5 | Activate ball valve control system (East wall) Red indicator lamp on | | Activated | |
| 6 | Check 20" butterfly valve closed | | Closed | |
| 7 | Check 12" butterfly bypass valve closed | | Closed | |
| 8 | Close drain valves (2) on bottom of outside pipeline | | Closed | |
| 9 | Walk to valve house outside of the lab and crack the ball valve open | | Cracked open | |
| 10 | Venturi meter 1" drain valve | V6a | Closed | |
| 11 | Wait for air-relief valves near V1 and at the bifurcation to stop discharging air | | Pipeline air bled | |
| 12 | Crack 20" butterfly valve and allow pipeline to fill slowly to the Rotovalve | | Cracked open | |
| 13 | Open vents on top of venturi (2) and just upstream of the Rotovalve (1) | | Vents open | |
| 14 | Close vent valves (3) opened in Step 10 once air has been vented from the pipeline | | Vents closed | |
| 15 | Allow pipeline to pressurize completely, then open 20" butterfly valve fully | | Fully open | |
| 16 | Set ball valve to desired position for turbine operation | | | |

## PRE-OPERATION INSPECTION

| Step | Item | Number | Condition | Checked? |
|---|---|---|---|---|
| 1 | Main laboratory pipeline filled | | Filled | |
| 2 | Open turbine bearing cooling water valve to obtain 90 psi downstream of filters, check pressure drop across filters, then close valve. If pressure drop is excessive, replace AMF Cuno water filters | V6b | $\Delta p \leq 20$ psi<br>G33 = _____<br>G34 = 90 psi | |
| 3 | Oil mist lubricators air supply valve | V10 | Closed | |
| 4 | Service air compressor<br>Quick-Connect air hose to oil mist air supply hose<br>Check for automatic operation and p > 100 psi<br>Drain filters and check crankcase oil | | Serviced | |
| 5 | Open wooden gate to allow sump discharge into culverts | | Fully open | |
| 6 | Visually check 18" butterfly valve on discharge line | | Fully open | |
| 7 | Open piezometer rings at bottom of penstock and toe of draft tube | | Open | |
| 8 | Plug in and turn on three signal conditioners | | On | |
| 9 | Thrust relief valve (on draft tube) | | Open | |
| 10 | Rotate turbine shaft by hand | | Free rotation | |
| 11 | Air injection red valve | | Closed | |
| 12 | Air injection valve V32 | V32 | Closed | |
| | Tailwater Tank | | | |
| 13 | Gageline shutoff valve | V38 | Open | |
| 14 | Pressure gage (G5) cock | G5L | Open | |
| 15 | Pressure gage (G5) blowoff cock | G5U | Open | |
| 16 | Pressure switch (G6 - TTPS) cock | G6L | Open | |
| 17 | Pressure switch (G6 - TTPS) blowoff cock | G6U | Closed | |
| 18 | Compressed air supply valve | V16 | Closed | |
| 19 | Compressed air valve | V18 | Closed | |
| 20 | Compressed air blowoff valve | V17 | Closed | |
| 21 | Sight gage upper valve | G24U | Open | |
| 22 | Sight gage lower valve | G24L | Open | |
| 23 | Tailwater tank drain valve | V9 | Closed | |
| | Valve Control Panels | | | |
| 24 | Rotovalve controller panel (downstairs) | | ON/AUTO | |
| 25 | Butterfly valve controller panel (downstairs) | | ON | |

| Step | Item | Number | Condition | Checked? |
|---|---|---|---|---|
| | Head Tank | | | |
| 26 | Head tank drain valve | V8 | Closed | |
| 27 | Head tank gageline shutoff valve | V37 | Open | |
| 28 | Pressure gage (G3) cock | G3L | Open | |
| 29 | Pressure gage (G3) blowoff cock | G3U | Open | |
| 30 | Pressure switch (G4 - HTPS) cock | G4L | Open | |
| 31 | Pressure switch (G4 - HTPS) blowoff cock | G4U | Closed | |
| 32 | High pressure air blowoff | V21 | Closed | |
| 33 | High pressure air valve | V22 | Closed | |
| 34 | High pressure air valve | V23 | Closed | |
| 35 | High pressure air valve | V25 | Closed | |
| 36 | Slight gage valve (upper) | G25U | Open | |
| 37 | Slight gage valve (lower) | G25L | Open | |
| 38 | 1-inch air vent shutoff valve | V27 | Open | |
| | Oil Mist Systems | | | |
| 39 | Dynamometer lower bearing oil supply strainer drain | | Clean | |
| 40 | Record dynamometer lower bearing oil supply reservoir level | | Filled | |
| 41 | Turbine bearing oil supply strainer drain | | Clean | |
| 42 | Record turbine bearing oil supply reservoir level | | Filled | |
| 43 | Dynamometer upper bearing oil supply strainer drain | | Clean | |
| 44 | Record dynamometer upper bearing oil supply reservoir level | | Filled | |
| | Miscellaneous | | | |
| 45 | Dynamometer cooling water tank drain valve | V40 | Closed | |
| 46 | Dynamometer cooling water strainer drains (3) | | Cleaned | |
| | Instrument Booth | | | |
| 47 | Head gage bleed valve | | Closed | |
| 48 | Tailwater gage bleed valve | | Closed | |
| 49 | Power supply circuit breakers | C1, C2 | Open circuit | |
| 50 | Dynamometer speed and current control potentiometers | | Zeroed | |

**GRAND COULEE THIRD POWERPLANT - TURBINE MODEL TEST FACILITY**
**COLORADO STATE UNIVERSITY - FORT COLLINS, COLORADO**
**ENGINEERING RESEARCH CENTER - HYDROMACHINERY LABORATORY**

## SETUP FOR OPERATION

| Step | Item | Number | Condition | Checked? |
|---|---|---|---|---|
| | PRE-OPERATION INSPECTION | | Completed | |
| 1 | Call Jerry Davis at ERC shop to have main lab guard valve opened | | | |
| | Instrument Booth Operations | | | |
| 2 | Scroll case inlet pressure transducer | | Calibrate | |
| 3 | Tailwater pressure transducer | | Calibrate | |
| 4 | Venturi differential pressure measurement system | | Bleed and Pressurize | |
| 5 | Venturi pressure transducer | | Calibrate | |
| 6 | Power supply circuit breaker | C-1 | Closed | |
| 7 | Dynamometer torque indicator switch | | Run | |
| 8 | Dynamometer torque indicator power switch | | Power | |
| 9 | Dynamometer speed counter switch | | On | |
| 10 | AC LINE ON white light<br>EMERGENCY WATER ON red light<br>UPPER BEARING OIL PRESSURE LOW light<br>LOWER BEARING OIL PRESSURE LOW light<br>TURBINE OIL PRESSURE LOW light<br>BEARING WATER PRESSURE LOW light<br>All other panel control lights | | On<br>On<br>On<br>On<br>On<br>On<br>Off | |
| 11 | Check and adjust torque indicator using 50 lb weights | | Adjusted | |
| | Valve Control Panel | | | |
| 12 | Butterfly valve BV<br>BV OPEN red light<br>BV CLOSED amber light | | Fully open<br>On<br>Off | |
| 13 | Audible alarm bell switch<br>BELL RINGS: 1. Head tank overpressure (185 psi)<br>2. Tail tank overpressure (20 psi)<br>3. Butterfly valve 90% closed<br>4. Dynamometer cooling water supply failure (p < 11 psi upstream of modulating valve)<br>5. Turbine overspeed circuit activates | | On | |

| | | | | |
|---|---|---|---|---|
| | Model Turbine Area | | | |
| 14 | Set wicket gates to desired position | | Set | |
| 15 | Turbine carbon bearing cooling water - open to 90 - 95 psi downstream of filters | V6b | Open | |
| 16 | Record pressures on G33 and G34 | | | |
| 17 | 2" dynamometer cooling water supply valve | V1 | Open | |
| 18 | Bearing water drain tube at turbine | | Flow | |
| 19 | Water discharge to sump/tailrace | | Audible | |
| 20 | Record dynamometer water supply pressure | G12 | 17 psi minimum | |
| 21 | Record bearing water pressure switch gage | G35 | 55 psi minimum | |
| | Oil Mist Systems | | | |
| 22 | Oil mist system compressed air supply valve | V10 | Open | |
| 23 | Adjust regulators on oil mist units to obtain visible flow of mist from discharge tubes. Oil mist pressure for all three units should be in the range of 24 - 26 inches of the water. | | Adjusted | |
| 24 | Record air supply and oil mist pressures for each unit | | | |
| 25 | Check all mist exhaust tubes (3) | | Visible mist | |

## START OPERATION

| Step | Item | Number | Condition | Checked? |
|---|---|---|---|---|
| 1 | SETUP FOR OPERATION checklist | | Completed | |
| 2 | Dynamometer thermocouple temperatures (about 55°F) | | No. 1 ______<br>No. 3 ______ | |
| 3 | AC LINE ON white light | | On | |
| 4 | Dynamometer LIGHT/HEAVY load selector | | Heavy | |
| 5 | Dynamometer cooling water pump -<br>push PUMP MOTOR ON button<br>PUMP MOTOR ON red light<br>EMERGENCY WATER ON red light | | <br><br>On<br>Off | |
| 6 | Butterfly valve BV<br>BV OPEN red light<br>BV CLOSED amber light | | Fully open<br>On<br>Off | |
| 7 | Rotovalve power supply circuit breaker | C-2 | Closed | |
| 8 | Rotovalve RV - Check gage on Valve Control Panel (0°)<br>RV CLOSED amber light<br>RV OPEN red light | | Fully Closed<br>On<br>Off | |
| 9 | Dynamometer SPEED CONTROL Setting | | 300 units | |
| 10 | Dynamometer CURRENT CONTROL setting | | 0 | |
| 11 | Set torque indicator zero | | 0 | |
| 12 | Calibrate torque readout with "Cal" button on panel | | 500 | |
| 13 | Record turbine operation starting time in daily log entry | | Recorded | |
| 14 | Open Rotovalve in small increments to adjust turbine speed to 500 rpm. Allow time for flow through system.<br>RV OPEN red light<br>RV CLOSED green light | | 500 rpm<br>Comes on<br>Remains on | |
| 15 | When speed reaches 500 rpm, press EXCITATION ON pushbutton<br>EXCITATION ON red light | | On<br>On | |
| 16 | Slowly increase excitation to 5% (with current control dial) and open Rotovalve to maintain not less than 1000 rpm. Adjust speed control as required | | Completed | |
| 17 | Check speed calibration and change calibration factor as required | | Calibrated | |
| 18 | Adjust butterfly valve for initial tailwater condition | | Adjusted | |
| 19 | Bleed transducers | | Completed | |

On completion of the above, the facility will be in operation. Operate Rotovalve, butterfly valve, speed and/or current controls as required to establish test conditions. OPERATOR AND BYPASS VALVE CONTROLLERS WILL REMAIN IN ATTENDANCE TO COMPLETE EMERGENCY SHUTDOWN, IF REQUIRED.

## SHUTDOWN PROCEDURE

| Step | Item | Number | Condition | Checked? |
|---|---|---|---|---|
| | Instrument Booth Operations | | | |
| 1 | Close Rotovalve slowly<br>RV CLOSED green light<br>RV OPEN red light | V35 | Fully closed<br>On<br>Off | |
| 2 | Brake to about 500 rpm with speed control | | 500 rpm | |
| 3 | When speed decreases to 500 rpm, push EXCITATION OFF pushbutton<br>EXCITATION ON red light | | Off | |
| 4 | Shut off dynamometer cooling water pump<br>EMERGENCY WATER ON red light | | Off<br>On | |
| 5 | 18-inch butterfly valve<br>BV OPEN red light<br>BV CLOSED green light | V36 | Fully open<br>On<br>Off | |
| 6 | Speed counter switch | | Off | |
| 7 | Dynamometer torque indicator switch | | Standby | |
| 8 | Dynamometer torque indicator power switch | | Off | |
| 9 | Power supply circuit breakers | C1, C2 | Open | |
| 10 | Record time of turbine shutdown and make operating log entry for day's operation | | | |
| | Turbine Area | | | |
| 11 | Compressed air supply valve | V10 | Closed | |
| 12 | 2-inch dynamometer cooling water supply valve | V1 | Closed | |
| 13 | Turbine bearing lubrication water | V6b | Closed | |
| 14 | 20" butterfly valve (downstream of bifurcation) | | Closed | |
| 15 | Close sump discharge gate | | Fully closed | |
| 16 | Tailwater tank drain valve | V9 | Open | |
| 17 | Head tank drain valve | V8 | Open | |
| 18 | Penstock and scroll case drain cock | | Open | |
| 19 | Relieve pressure in inlet pipe using venturi blowoff cocks | | | |
| 20 | Walk to valve house and close ball valve | | Closed | |
| 21 | Deactivate ball valve control system (East wall)<br>Red indicator light | | Off | |
| 22 | Call ERC shop to close main lab guard valve | | | |
| 23 | Open drain valves on outside pipeline | | Drains open | |

# APPENDIX B

## Emergency Procedures for Turbine Test Facility

## EMERGENCY PROCEDURES FOR TURBINE TEST FACILITY

The general emergency procedure for the test facility is to stop the flow through the turbine model as quickly as possible and to then remove power from all circuits. This must be done either through operation of the Rotovalve or the emergency bypass.

### Power Outages

**Complete loss of power.** - In the event of a total power outage, excitation will be removed from the dynamometer, allowing the turbine to reach runaway speed. In order to prevent runaway and damage to the turbine model and test facility, the emergency bypass must be opened immediately. Do not attempt to manually close the Rotovalve. During turbine runaway, the area around the turbine model may be very dangerous due to flying debris.

If two persons are available to operate the emergency bypass, then one person should open the 10-in butterfly bypass valve while the second person closes the 20-in butterfly shutoff valve. This operation should be completed as quickly as possible. If only one person is available the 10-in bypass should be opened fully, then the 20-in butterfly should be closed fully.

Once the 20-in butterfly valve is fully closed, then the 10-in bypass should be closed. This should be done slowly to prevent water hammer. Also, as an added precaution, the Rotovalve may be closed manually once the turbine has coasted to a stop. The ball valve outside the laboratory can not be closed until electric power is restored. If power is still available at the main lab, the guard valve at the main lab should be closed.

Once shutdown has been completed, circuit breaker C1 should be set to the open circuit position. This will prevent excitation from being reapplied to the dynamometer when power is restored. Also, the next time that circuit C1 is closed, the operator should be prepared to immediately press the EXCITATION OFF button, to prevent burning up the excitation circuit.

**Loss of power to dynamometer circuit only.** - If power is lost on the dynamometer circuit C1 only, the turbine will begin to overspeed. Because the overspeed shutdown circuit is powered from C1, it will be inoperative and the turbine will reach runaway speed. The Rotovalve should be closed from the valve control panel in the control room as quickly as possible. Also, the emergency bypass should be opened simultaneously by a second person to dissipate water hammer. Again, circuit C1 should be opened at the breaker, in case power is restored after the dynamometer has stopped turning.

**Loss of power to Rotovalve circuit only.** - Loss of power to the Rotovalve circuit C2 will require that the Rotovalve be closed manually. Control may still be exercised over the turbine. The operator should remain in the control room to apply braking power to the turbine as the Rotovalve is manually closed.

**Tripping of C1 or C2 circuit breakers.** - Tripping of the C1 circuit breaker will produce the same effect as the loss of power to the dynamometer circuit. In order to restore power to the C1 circuit, the operator should immediately attempt to reset the C1 breaker. If the reset attempt is not successful, this should be treated as a power outage using the appropriate procedure above. Tripping of the C2 circuit breaker is not normally a serious problem, unless the Rotovalve is currently being closed as part of an emergency shutdown.

## Removal of Dynamometer Excitation by the Protective Circuit

The protective circuitry of the dynamometer will remove excitation from the dynamometer if either of the following conditions occur.

1. Cooling water temperature at the manifold on the exit side of the dynamometer exceeds 165 °F.

2. Cooling water pressure measured by pressure switch G34 (located at the manifold on the inlet side of the dynamometer) detects low pressure in cooling water supply line. This switch is set to open on falling pressure of 20 $lb/in^2$ and close on rising pressure of 21 $lb/in^2$.

This will cause the unit to overspeed, eventually triggering the overspeed circuit which will close the Rotovalve. If the overspeed circuit is not functioning properly, these situations can lead to turbine runaway and should be handled using the procedures above for a power outage on the dynamometer circuit.

## Low Carbon Bearing Cooling Water Pressure

The pressure switch (BWPS) for the carbon bearing cooling water supply is located to the left of the oil mist units. When pressure drops too low the switch will open making it impossible to further open the Rotovalve from the control room. The BEARING WATER LOW PRESSURE light will come on in the control room. The BWPS pressure can be low for a variety of reasons.

If the BWPS light comes on during startup of the unit, it is an indication that an upstream valve has not yet been opened fully. In this case the unit should be shut down by closing the Rotovalve, and the problem then corrected.

The BWPS light may also come on due to falling static head from Horsetooth Reservoir. In this case the pressure indicated on the BWPS gauge will be just slightly below the switch setting. If sufficient water flow is still being maintained through the carbon sleeve bearing, then the pressure switch can be manually adjusted downward to allow for operation at the lower reservoir level. The switch is currently (September 1989) set to trip at about 55 $lb/in^2$.

The last possible cause of pressure loss at BWPS is plugging of the AMF Cuno filters. This can be a serious problem if flow through the carbon sleeve bearing is greatly diminished and would require that the unit be immediately shut down from the control room. A plugged filter will be indicated by a large pressure drop across the filter.

A general procedure for handling problems with the BWPS light is as follows. Any time the BWPS light comes on, the operator should immediately check the reading on the BWPS gauge and observe the flow through the sleeve bearing. If the pressure is very low or the flow greatly diminished, the unit should be shut down immediately.

## Low Oil Mist Pressure

Oil mist pressure lights are located on the dynamometer control console. If only one light comes on, the operator should immediately check the gauge readings on the oil mist unit in question. A very low reading on the oil mist pressure (less than 15 in of water) calls for immediate shut down of the unit, before the bearing is damaged.

If more than one oil mist pressure light comes on simultaneously, it is an indication of a failure in the air supply system. The facility should be shut down immediately.

### Low Oil Mist Levels

If any of the three oil mist reservoirs becomes low the respective oil level light in the control room will be lit. Oil must be added to the reservoir immediately to ensure proper bearing lubrication.

### Excessive Heating

**Dynamometer inductor ring.** - Continued heating of the dynamometer inductor ring at constant load indicates scale buildup in the dynamometer. This is not an emergency situation unless the cooling water temperatures are also becoming extreme. The unit should be shut down and the dynamometer descaled according to instructions in the Dynamatic manual.

**Dynamometer cooling water.** - The temperature of the cooling water exiting the dynamometer is monitored by a temperature switch, G15, and two thermocouples, one T-type monitored by the HP85, and a J-type monitored on the control console. When the cooling water temperature exceeds 130 °F the cooling capacity of the system can not increase further, and the cooling water temperature will probably continue to increase. At 165 °F dynamometer excitation will be removed, and the turbine will overspeed, causing automatic closure of the Rotovalve. To prevent this sudden shutdown of the unit, the cooling water temperature should be monitored closely. Any time the temperature exceeds 130 °F, the unit should be shut down.

### Alarm Bell

Each of the following conditions will cause the audible alarm bell to sound in the control room.

1. Pressure less than 11 lb/in$^2$ at pressure switch G13. Switch G13 is located just upstream of the temperature controlled modulating valve. Inadequate pressure at G13 should be considered an early warning of a serious problem in the cooling water circuit. An immediate shutdown of the facility should be performed from the control room.

2. Butterfly valve 90 percent closed. Immediately open the butterfly valve. Note: A pressure indication of more than about 14 ft of water on the tailwater gauge located in the control room indicates that water is being discharged through the top of the standpipe.

3. Head tank overpressure (185 lb/in$^2$ = 427 ft of water)

4. Tailwater tank overpressure (20 lb/in$^2$ = 46.2 ft of water)

5. Activation of the overspeed circuit. If the turbine speed exceeds 3,350 r/min, the overspeed circuit will automatically begin closure of the Rotovalve. When the turbine speed drops to 2,300 r/min, closure of the Rotovalve will be stopped. Under low loads, such as a No Load Test, the Rotovalve will be completely closed before the turbine coasts down to 2,300 r/min.

## Electrical Problems or Fire

Any electrical problems in the console or valve control panel call for an immediate shutdown of the facility. The potential for fire associated with electrical problems requires that the shutdown be performed as quickly as possible, in case a fire should cause loss of control of the dynamometer or Rotovalve. Assuming control of the dynamometer and Rotovalve are still available, the shutdown can be performed from the control room.

# APPENDIX C

## Cooling System Operation

## INTRODUCTION

On April 14, 1989, tests were conducted to evaluate turbine operation at high load, check operation of cooling water systems and verify structural stability in rough operating zones. During the run, temperatures indicated on thermocouple meter G10 on the dynamometer control console reached about 130° F. This temperature seemed much too high, given the light load on the turbine of about 150 hp. Also, a note at the bottom of the LOAD TEST RECORD data sheet indicated that no temperature should exceed 120° F. To check operation of the temperature modulation valve V5, the stem position of the valve was checked just before shutdown and again after shutdown. The valve did not appear to have moved significantly.

To more accurately check the operation of V5, the temperature probe for the valve was removed from the dynamometer return water circuit. The probe was alternately placed in hot water (about 125 °F) and cold tap water. A stem movement of about 5/32 in was measured. This appeared to be consistent with the manufacturer's literature for the valve, and the probe was reinstalled.

In subsequent weeks the turbine was run at loads up to 200 hp. During these runs the maximum temperature indicated on meter G10 was 130 °F. By this time, the data acquisition system was up and running. One function of the program was to monitor a T-type thermocouple just recently installed at the dynamometer cooling water discharge manifold. This thermocouple had been installed in an existing probe on the discharge manifold. This probe had originally been a J-type thermocouple but was damaged in shipment. During runs in which 130 °F was indicated by G10, the T-type thermocouple never indicated higher than 95 °F.

On July 10 an attempt was made to reach a very low sigma value by operating at heads up to 180 feet. During this run, the turbine output reached 227 hp. The highest temperature indicated on G10 was 135 °F, while the T-type thermocouple reached only 94°F. Also, during this run, a mercury thermometer was used to measure the temperature of the cooling water discharged to the sump. This temperature was 81 °F.

At this point, it was determined that there were problems with the cooling system or problems with our understanding of its operation. In either case, the problems were limiting the ability to carry out testing at low sigma values. An investigation of the cooling water system operation and the associated monitoring equipment was undertaken.

## GENERAL OPERATION

Flow is started through the cooling system by opening 2-in supply valve V1. Solenoid valves V2 and V3 are initially open and closed, respectively (see Reclamation drawings 1222-D-1536 and 1222-D-1537). Flow is through V2, through the dynamometer water jacket and back to the dynamometer cooling water recirculating tank. This tank then overflows and dumps into the sump. This circuit serves as the emergency cooling circuit in case of failure of the cooling water pump.

The normal recirculation system is energized by pushing the PUMP MOTOR ON button on the dynamometer control console. When this button is pushed V3 opens and V2 closes. Water flow is now through V3. Water then flows through constant flow valve V4 (7 gal/min) and into the cooling water tank, where it mixes with warm water returning from the dynamometer. The pump delivers water from this tank, through the dynamometer, and back to the tank. Seven gal/min will overflow the weir inside the tank and be discharged to the sump.

As load on the dynamometer is increased, the cooling water temperature will increase. This temperature is monitored by a T-type thermocouple located on the dynamometer cooling water discharge manifold (Dynamatic C-62497, D-62388, 15-177-9D), a temperature switch, G15 (USBR 1222-D-2404, 2405) located on the same manifold, and an inert gas temperature probe located on the 4-inch cooling water return line. The T-type thermocouple is monitored by the data acquisition system. Temperature switch G15 controls the dynamometer excitation circuit. The inert gas probe controls the modulating valve V5, which is in parallel with the 7-gal/min constant flow valve, V4. When the temperature reaches 90 °F, the modulating valve V5 begins to open, allowing additional cold water to enter the cooling water tank. When the temperature at the probe reaches 130 °F, the modulating valve will be fully open. At this point, the maximum cooling capacity has been reached. If the temperature in the circuit should continue to rise, temperature switch G15 will open at 165 °F, removing excitation from the dynamometer and allowing the turbine to overspeed.

In addition to the three monitoring points along the dynamometer cooling water discharge line, three J-type thermocouples are installed inside the dynamometer on the inductor ring. These thermocouples are monitored by meter G10 on the dynamometer control console (see DOC, August 1974, pp. 17-19). Thermocouples 1 and 3 are connected to the selector switch just left of G10. Thermocouple 2 is inoperative. These are the thermocouples that were being monitored on April 14, 1989. They are only monitors and do not affect the excitation circuit in any way. The Dynamatic manual states that if the inductor ring temperature increases under constant load, then there is a problem with scale buildup in the cooling passages. However, no guidelines for normal or maximum operating temperatures are given.

## CONCLUSIONS

1. The modulating valve V5 works properly, as does the rest of the dynamometer cooling system. The reason that movement of the modulating valve could not be detected is that the valve was only slightly open, with a dynamometer cooling water discharge temperature of about 95 °F.

2. Temperatures of 120 to 150 °F are not abnormal for the inductor ring unless there appears to be a continuous temperature increase at constant load. During recent runs at loads up to 290 hp (near the upper limit of capacity during the summer of 1989 due to drawdown of Horsetooth Reservoir), inductor ring temperatures of 145 °F have been noted, but at no time has the cooling water discharge temperature exceeded 96 °F.

3. The inductor ring temperature is only an indication of the scale buildup within the dynamometer cooling passages.

4. The temperature monitored by temperature switch G15 and the T-type thermocouple is the indicator of proper cooling system operation. This is the critical temperature for maintaining excitation current to the dynamometer.

5. The 120 °F limit referred to on the LOAD TEST RECORD data sheet should only apply to the dynamometer cooling water discharge temperature, not the inductor ring temperatures.

6. To improve the monitoring of cooling water temperatures, several changes were made following this investigation: (1) All thermocouple meters were labeled according to sensor locations and the control functions of those sensors; (2) A J-type thermocouple was installed in the dynamometer cooling water discharge manifold and connected to meter G11. This was the original configuration for monitoring the cooling water temperature, but was poorly documented in the Dynamatic and USBR schematics; and (3) the data acquisition program was modified to give a warning alarm when cooling water temperature exceeds 120 °F.

# APPENDIX D

## Pressure Switches and Controls

## HTPS - G4 - Head Tank Pressure Switch

Drawings

USBR 1222-D-1536, 1537, 2402, 2404, 2405

Location

Face of gage panel at side of head tank.

Function

1. Prevent excessive pressure in head tank (design pressure 250 psi)
2. Actuate alarm bell at high pressure limit of head tank

Operation

The pressure switch monitors head tank pressure. Pressure is controlled by throttling Rotovalve (V35). If the setting of the Rotovalve allows the tank pressure to exceed 185 psi, one set of contacts opens the Rotovalve OPEN circuit, preventing further increases in pressure, and the second set of contacts closes, actuating the alarm bell on the valve control panel in the control room. Pressure in tank is also monitored by gage G3 on the head tank gage panel and gage G1 on the control room valve control panel.

Setting

1. Rotovalve OPEN circuit
   - Increasing pressure
     - 0 to 185 psi - CLOSED
     - 185 psi and higher - OPEN
   - Decreasing pressure
     - 160 psi and higher - OPEN
     - 0 to 160 psi - CLOSED

2. Alarm circuit
   - Increasing pressure
     - 0 to 185 psi - OPEN
     - 185 psi and higher - CLOSED
   - Decreasing pressure
     - 160 psi and higher - CLOSED
     - 0 to 160 psi - OPEN

## TTPS - G6 - Tailwater Tank Pressure Switch

Drawings

USBR 1222-D-1536, 1537, 2403, 2404, 2405

Location

Face of gage panel at side of tailwater tank.

Function

1. Prevent excessive pressure in tailwater tank (design pressure 50 psi)
2. Actuate alarm bell at high pressure limit of tailwater tank

Operation

The pressure switch monitors tailwater tank pressure. Pressure is adjusted by throttling of the 18 inch butterfly valve (V36). If the setting of the valve allows the tank pressure to exceed 20 psi (46.2 feet of water), one set of contacts opens the butterfly valve CLOSE circuit, preventing further increases in pressure, and the second set of contacts closes, actuating the alarm bell on the valve control panel in the control room. Pressure in tank is also monitored by gage G5 on the tailwater tank gage panel and gage G2 on the control room valve control panel.

Setting

1. Butterfly valve CLOSE circuit
   - Increasing pressure
     - 0 to 20 psi - CLOSED
     - 20 psi and higher - OPEN
   - Decreasing pressure
     - 15 psi and higher - OPEN
     - 0 to 15 psi - CLOSED

2. Alarm circuit
   - Increasing pressure
     - 0 to 20 psi - OPEN
     - 20 psi and higher - CLOSED
   - Decreasing pressure
     - 15 psi and higher - CLOSED
     - 0 to 15 psi - OPEN

## G13 - Cooling Water Supply Pressure Switch

Drawings

USBR 1222-D-1537, 2404, 2405
Dynamatic EC-19085,D-62388
United Electric Controls J41

Location

On electrical junction box on pump side (south) of recirculating system water tank.

Function

Actuate alarm bell when low pressure is detected in water supply for dynamometer cooling water recirculation system.

Operation

Water is supplied to the dynamometer cooling system from the 2 inch line coming off of 24 inch line running parallel to turbine test facility. The 2 inch line is controlled by valve V1. The pressure switch monitors the pressure of this water supply. If pressure is 11 psi or lower, contacts close and actuate alarm bell in control room. Pressure at G13 is also monitored by gage G12 located on recirculation system piping downstream of cooling water pump.

Setting

Alarm
- Increasing pressure
  - 0 to 12 psi - CLOSED
  - 11 psi and higher - OPEN
- Decreasing pressure
  - 11 psi and higher - OPEN
  - 0 to 11 psi - CLOSED

## G14 - Recirculation Pump Discharge Pressure Switch

Drawings

USBR 1222-D-1537, 2404, 2405
Dynamatic EC-19085, D-62388
United Electric Controls J41

Location

On electrical junction box on pump side (south) of recirculating system water tank.

Function

1. Prevent dynamometer overheating resulting from failure of water supply from recirculating system pump.
2. Actuate EMERGENCY WATER ON signal light at failure of pump discharge pressure.

Operation

Water is recirculated by the cooling water pump from the tank, through the dynamometer cooling passages and back to the cooling water tank. The pressure switch monitors the pump discharge pressure. Pressure at G14 is also monitored by gage G12 located on recirculation system piping downstream of cooling water pump.

1. If pressure is 28 psi or lower, the first set of contacts opens, permitting the normally open emergency water supply solenoid valve V2 to open, preventing failure of water supply to the dynamometer, and opening the Rotovalve OPEN circuit through relay PLP. Also, normally closed solenoid valve V3 is closed.
2. The second set of contacts closes at 28 psi or lower to light the red EMERGENCY WATER ON light at the dynamometer control console.

Setting

1) Solenoid valve/Rotovalve control
- Increasing pressure
  - 0 to 29 psi - OPEN
  - 29 psi and higher - CLOSED
- Decreasing pressure
  - 28 psi and higher - CLOSED
  - 0 to 160 psi - OPEN

2) Alarm circuit
- Increasing pressure
  - 0 to 185 psi - OPEN
  - 185 psi and higher - CLOSED
- Decreasing pressure
  - 160 psi and higher - CLOSED
  - 0 to 28 psi - OPEN

## G15 - Dynamometer Discharge Temperature Switch

Drawings

USBR 1222-D-1537, 2404, 2405
Dynamatic C-62497, C-62391, C-62392, 15-177-9D

Location

In small terminal box located on dynamometer cooling water discharge manifold.

Function

Prevent excessive temperature in dynamometer due to inadequate cooling capacity.

Operation

The temperature switch monitors the temperature of cooling water discharged from the cooling passages of the dynamometer. This temperature is also monitored by a T-type thermocouple connected to the HP85 computer and a J-type thermocouple connected to meter G11 (Dynamatic Drawing 15-177-9D) on the dynamometer control console. The switch is normally closed. If the temperature exceeds 165°F the switch opens, removing excitation from the dynamometer. This will cause the unit to overspeed, and the overspeed relay circuit will initiate automatic emergency closure of the Rotovalve at a speed of 3350 rpm.

Setting

Dynamometer excitation circuit
    Increasing temperature
        0 to 165°F - CLOSED
        165°F and higher - OPEN

## Overspeed Relay

Drawings

USBR 1222-D-2402, 2405
Dynamatic C-62391

Location

Bottom compartment of dynamometer control console.

Function

Prevent runaway of model turbine.

Operation

The overspeed relay receives a speed signal from a pulse tachometer located just above the upper dynamometer trunnion bearing. If the speed exceeds 3350 rpm the relay closes, initiating automatic emergency closure of the Rotovalve, and activating the alarm bell on the valve control panel in the control room. The overspeed circuit can be adjusted using the potentiometer located on the unit. The potentiometers are currently set for a speed setting of 30 and an acceleration setting of 47.

Setting

Rotovalve CLOSE circuit and alarm bell circuit
    0 to 3350 rpm - OPEN
    3350 rpm and higher - CLOSED

## G18u - Upper Dynamometer Oil Mist Pressure Switch

Drawings

USBR 1222-D-1537, 2404, 2405
Dynamatic EC-19085, B-62394

Location

On electrical junction box on downstream side of dynamometer.

Function

Prevent failure of upper dynamometer precision bearing (rotor bearing) due to insufficient lubrication oil mist pressure

Operation

Compressed air is supplied to the oil mist unit where its pressure is reduced to about 35 psi. This air then passes through a venturi, picking up oil from the reservoir. The oil mist then passes through the supply lines to the upper dynamometer precision bearing. If the mist pressure is 10 in. of water or lower, contacts close and light the amber UPPER BEARING OIL PRESSURE LOW light on the dynamometer control panel. The mist pressure is also monitored by gage G17u mounted on the oil mist unit.

Setting

UPPER BEARING OIL PRESSURE LOW light
- Increasing pressure
  - 0 to 10 in. water - CLOSED
  - 10 in. water and higher - OPEN
- Decreasing pressure
  - 10 in. water and higher - OPEN
  - 0 to 10 in. water - CLOSED

## G18l - Lower Dynamometer Oil Mist Pressure Switch

Drawings

USBR 1222-D-1537, 2404, 2405
Dynamatic EC-19085, B-62394

Location

On lower dynamometer oil mist lubrication unit.

Function

Prevent failure of lower dynamometer precision bearing (rotor bearing) due to insufficient lubrication oil mist pressure

Operation

Compressed air is supplied to the oil mist unit where its pressure is reduced to about 20 psi. This air then passes through a venturi, picking up oil from the reservoir. The oil mist then passes through the supply lines to the lower dynamometer precision bearing. If the mist pressure is 10 in. of water or lower, contacts close and light the amber LOWER BEARING OIL PRESSURE LOW light on the dynamometer control panel. The mist pressure is also monitored by gage G17l mounted on the oil mist unit.

Setting

LOWER BEARING OIL PRESSURE LOW light
- Increasing pressure
  - 0 to 10 in. water - CLOSED
  - 10 in. water and higher - OPEN
- Decreasing pressure
  - 10 in. water and higher - OPEN
  - 0 to 10 in. water - CLOSED

## G19u - Upper Dynamometer Oil Mist Level Switch

Drawings

USBR 1222-D-1537, 2404, 2405
Dynamatic EC-19085, B-62394

Location

Upper dynamometer oil mist unit.

Function

Prevent failure of upper dynamometer precision bearing (rotor bearing) due to lack of oil in oil mist unit reservoir.

Operation

The level switch monitors the level of oil mist in the reservoir. If the level in the reservoir gets too low the switch will close, lighting the UPPER OIL MIST LEVEL LOW light on the dynamometer console. The level at which the switch closes has not been tested, although it has been verified that the switch is closed when the reservoir is empty.

## G19l - Lower Dynamometer Oil Mist Level Switch

Drawings

USBR 1222-D-1537, 2404, 2405
Dynamatic EC-19085, B-62394

Location

Lower dynamometer oil mist unit.

Function

Prevent failure of lower dynamometer precision bearing (rotor bearing) due to lack of oil in oil mist unit reservoir.

Operation

The level switch monitors the level of oil mist in the reservoir. If the level in the reservoir gets too low the switch will close, lighting the LOWER OIL MIST LEVEL LOW light on the dynamometer console. The level at which the switch closes has not been tested, although it has been verified that the switch is closed when the reservoir is empty.

## G22 - Turbine Oil Mist Pressure Switch

Drawings

USBR 1222-D-1537, 2404, 2405
Dynamatic EC-19085, B-62394

Location

On turbine oil mist lubrication unit.

Function

Prevent failure of turbine precision bearing due to insufficient lubrication oil mist pressure

Operation

Compressed air is supplied to the oil mist unit where its pressure is reduced to about 40 psi. This air then passes through a venturi, picking up oil from the reservoir. The oil mist then passes through the supply lines to the turbine precision bearing. If the mist pressure is 20 in. of water or lower, contacts close and light the amber TURBINE BEARING OIL PRESSURE LOW light on the dynamometer control panel. The mist pressure is also monitored by gage G21 mounted on the oil mist unit.

Setting

LOWER BEARING OIL PRESSURE LOW light
- Increasing pressure
  - 0 to 20 in. water - CLOSED
  - 20 in. water and higher - OPEN
- Decreasing pressure
  - 20 in. water and higher - OPEN
  - 0 to 20 in. water - CLOSED

## G23 - Turbine Oil Mist Level Switch

Drawings

USBR 1222-D-1537, 2404, 2405
Dynamatic EC-19085, B-62394

Location

Turbine oil mist unit.

Function

Prevent failure of turbine precision bearing due to lack of oil in oil mist unit reservoir.

Operation

The level switch monitors the level of oil mist in the reservoir. If the level in the reservoir gets too low the switch will close, lighting the TURBINE OIL MIST LEVEL LOW light on the dynamometer console. The level at which the switch closes has not been tested, although it has been verified that the switch is closed when the reservoir is empty.

## G34 - Dynamometer Inlet Manifold Pressure Switch

Drawings

USBR 1222-D-1537, 2404, 2405
Dynamatic EC-19085, C-62497
United Electric Controls J41

Location

On electrical junction box on downstream side of dynamometer.

Function

Prevent dynamometer overheating resulting from failure of water supply from recirculating and emergency systems.

Operation

Water is passed through the dynamometer passages by the recirculation pump from the cooling water tank or by the emergency straight through system relying on water pressure available from the 24 inch line running parallel to the test facility. The pressure switch monitors the pressure at the dynamometer inlet manifold. If this pressure is 20 psi or lower, then both the recirculating and emergency systems have failed. Contacts open, opening the dynamometer excitation circuit. This causes the unit to overspeed, and at 3350 rpm the overspeed relay will initiate automatic emergency closure of the Rotovalve.

Setting

Dynamometer excitation circuit
- Increasing pressure
  - 0 to 21 psi - OPEN
  - 21 psi and higher - CLOSED
- Decreasing pressure
  - 20 psi and higher - CLOSED
  - 0 to 20 psi - OPEN

## G35 - Bearing Water Pressure Switch

Drawings

USBR 1222-D-1537, 2404 (Shown as annotations on later versions of these drawings. Not indicated on earlier versions.)

Location

Left of oil mist lubrication units, on balcony overlooking penstock and dynamometer.

Function

Prevent failure of turbine carbon sleeve bearing due to insufficient cooling water pressure.

Operation

Water is supplied to the carbon sleeve bearing by 3/8-inch copper tubing leading from the 24 inch line parallel to the test facility. This water is filtered before reaching the carbon sleeve bearing. The pressure switch monitors the pressure in this line approximately 5 feet upstream of the bearing. At Estes Powerplant this switch was set to operate at 85 psi. Due to the lower heads available at the Hydromachinery Lab, this switch was reset to 57 psi on 4/19/89 during a site visit by Tom Isbester and Brent Mefford. Since that time, lowering of Horsetooth Reservoir has required that this switch be readjusted to operate at about 55 psi. The water flow through the carbon sleeve bearing is still about 2 gpm.
When the pressure falls below 55 psi the first set of contacts (circuit C1, RED, PURPLE, BLUE) opens, opening the Rotovalve OPEN circuit. The second set of contacts (circuit C2, BROWN, YELLOW, ORANGE) closes, activating the amber BEARING WATER LOW PRESSURE light.

Setting

1) Rotovalve OPEN circuit
- Increasing pressure
  - 0 to 60 psi - OPEN
  - 60 psi and higher - CLOSED
- Decreasing pressure
  - 55 psi and higher - CLOSED
  - 0 to 55 psi - OPEN

2) BEARING WATER LOW PRESSURE light
- Increasing pressure
  - 0 to 60 psi - CLOSED
  - 60 psi and higher - OPEN
- Decreasing pressure
  - 55 psi and higher - OPEN
  - 0 to 55 psi - CLOSED

# APPENDIX E

## Maintenance Operations

## OIL MIST AIR REGULATORS

During initial runs of the turbine, problems developed with shellac buildup within the oil mist air regulators. It was eventually determined that deteriorated oil in the oil mist reservoirs was the source of the problem. Eaton Corporation recommended three oil types suitable for the misters. They are:

1. Mobil DTE Medium-Heavy
2. Texaco Regal PC
3. Shell Tellus 33

Regal PC oil was obtained for use in the oil misters. The problem with sticking misters was corrected when the new air compressor was obtained.

Once a shellac has formed in the regulators, they tend to stick open at the beginning of each run. To restore proper operation the regulator must be disassembled and cleaned using a degreaser.

Disassembly of the regulators begins with the removal of the copper tubing connecting the mist unit sediment bowl to the regulator inlet (this need not be removed on the lower dynamometer bearing unit). Now remove the hand wheel and the spring behind it (the lower dynamometer bearing unit does not have a handwheel or spring). Next, remove the regulator cover plug, noting the depth to which it is set before removal. A stiff, steel spring and an aluminum end cap will come out with the cover plug. Now remove the steel washer and rubber diaphragm. Use a pair of pliers to carefully remove the plunger. At this point the parts should be thoroughly cleaned using a degreaser. Also clean the shellac from all surfaces that can be reached in the regulator.

Reassemble the unit in the reverse order. Take care when reinstalling the cover plug to make sure the spring and aluminum end cap are in proper alignment. If the cover plug does not seat back to the original depth, then either the spring or the large steel washer has slipped out of place.

## DYNAMOMETER BEARINGS

During installation of the unit, the top trunnion and precision bearings were examined. This required partial disassembly of the dynamometer. The disassembly procedure to reach the bottom bearings is identical, as the bearing arrangement on the bottom is a mirror image of the top. However, to gain access to the bottom bearings would require removal of the dynamometer from the test stand.

Disassembly began by removing the Servo-tech tachometer generator and cover plate. Next, the collar surrounding the permanent magnet generator was removed, and the permanent magnet generator was removed from the shaft. The top cover of the dynamometer housing was then unbolted and removed using a crane. The trunnion bearing was then removed from the shaft. Two cover plates were removed to expose the precision rotor bearing. Removal of the rotor bearings requires the use of a specially built gear puller. This gear puller was fabricated, but the excellent condition of the bearing prompted the decision to reassemble the dynamometer at this point. A series of photos is included at the end of this appendix showing the disassembly procedure.

## DISASSEMBLY OF TURBINE SHAFT FOR PERIODIC LUBRICATION

The turbine shaft was removed from the test stand to permit lubrication of the upper and lower floating couplings. The couplings were completely degreased and then repacked.

Figure E-1. - Dynamometer prior to dissassembly.

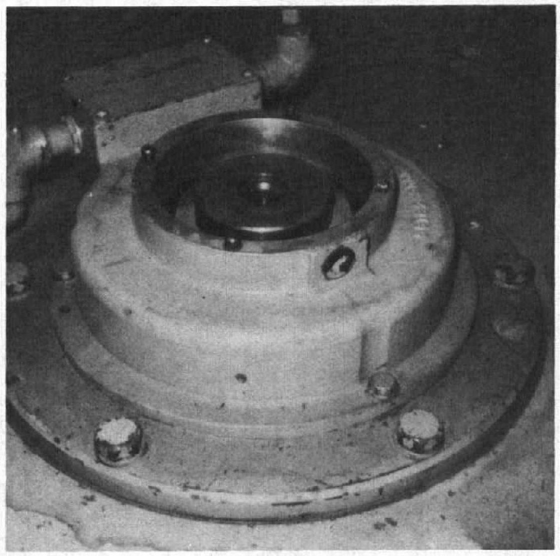


Figure E-2. - Cover plate removed to reveal tachometer generator.

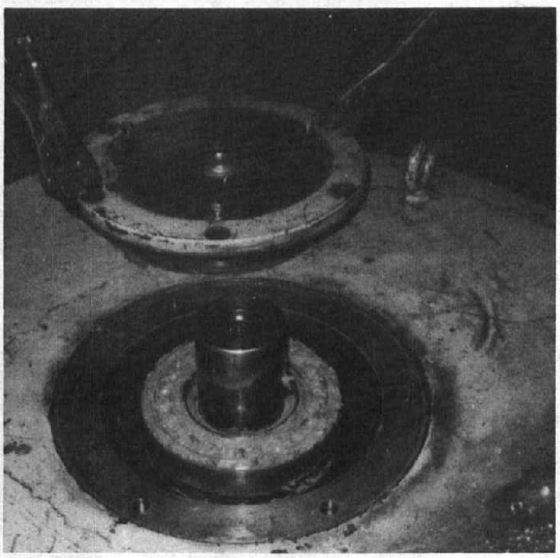


Figure E-3. - Cover removed to expose upper trunnion bearing

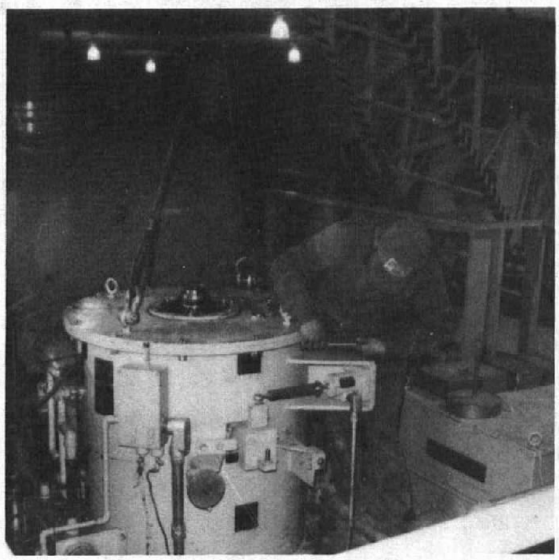


Figure E-4. - Removing top plate from the dynamometer.

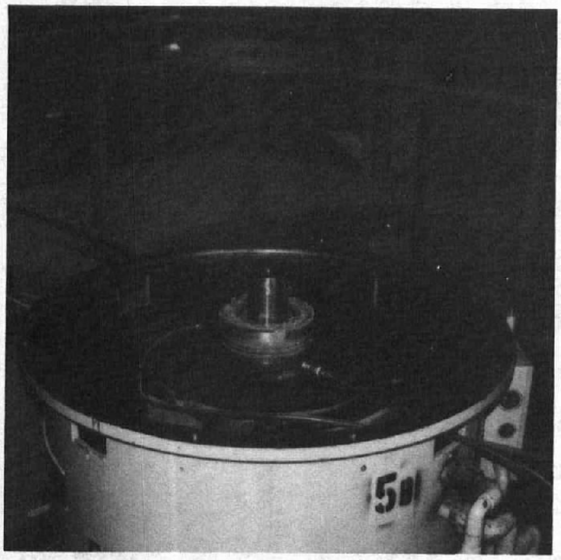


Figure E-5. - Top plate of the dynamometer removed. Oil mist is supplied to the top precision bearing through the copper tubing on the right. Oil mist exhaust from the bearing is drained through the flexible plastic tubing on the left.

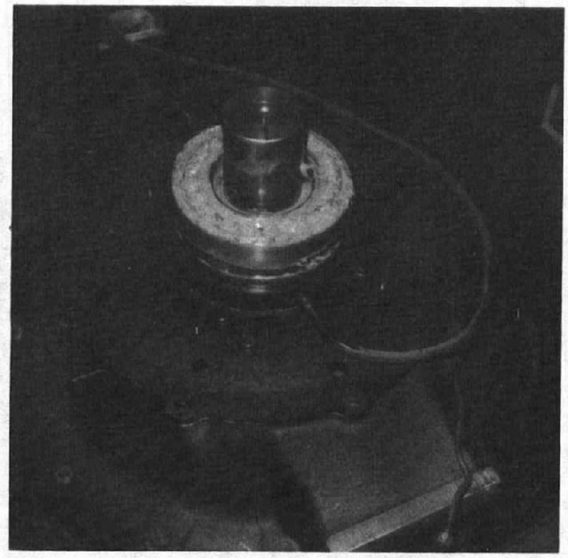


Figure E-6. - Closeup view of the trunnion bearing and oil mist lines.

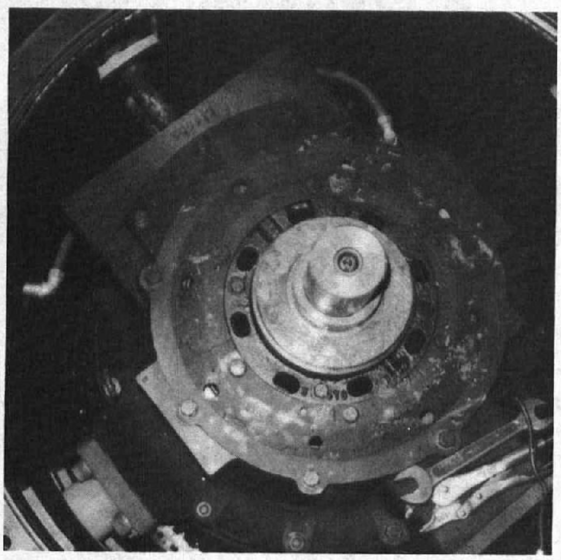


Figure E-7. - Trunnion bearing removed and oil mist lines disconnected.

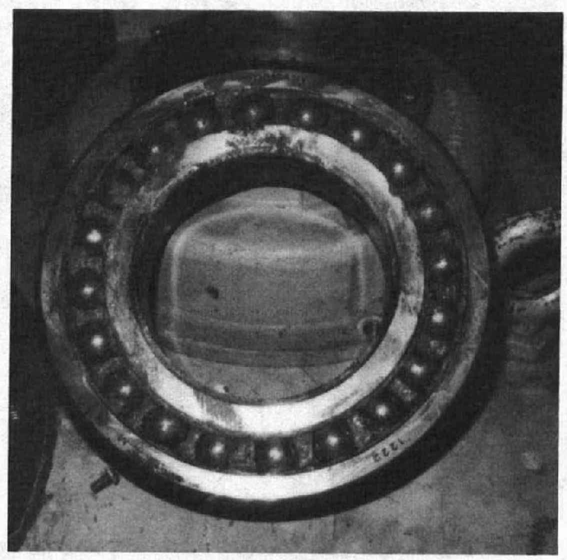


Figure E-8. - Dynamometer upper trunnion bearing following removal from the dynamometer.

Figure E-9. - Using supplied bolt jacks to lift the cap that covers the precision bearing.

Figure E-10. - Using a spanner wrench to remove the precision bearing retainer ring and nut.

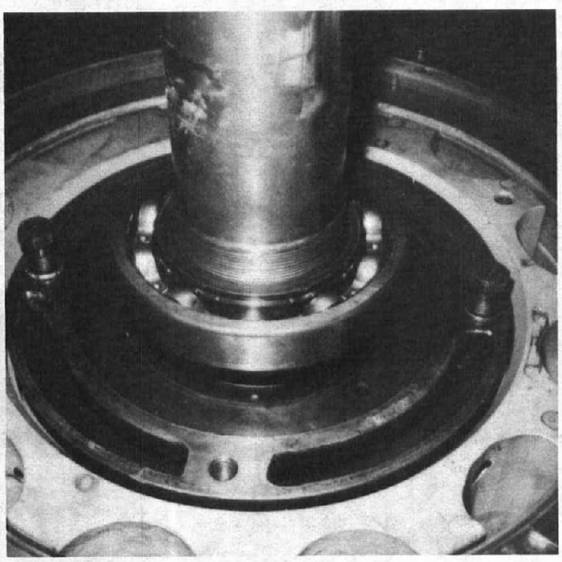


Figure E-11. - Dynamometer top precision bearing in place following removal of the retainer ring and nut.

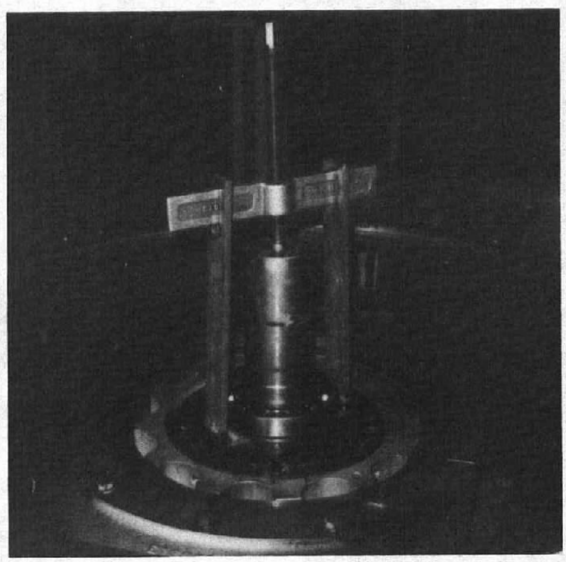


Figure E-12. - Bearing puller in place for removal of the precision bearing. The precision bearing was not removed.

## APPENDIX F

### Model Dimensions

## Allis Chalmers 1:40.3 Model Turbine
## Important Dimensions

### Spiral Case Pressure

An abrupt change in cross section occurs downstream of the spiral case flange. Use the penstock exit piezometer ring for the best measurement.

| | | |
|---|---|---|
| Spiral Case Inlet | 10.314 in diameter | Area = 0.5802 $ft^2$ |
| Spiral Case Ring | 10.414 in diameter | Area = 0.5915 $ft^2$ |
| Penstock Ring | 10.359 in diameter | Area = 0.5853 $ft^2$ |

### Draft Tube Area at Piezometer Taps

The draft tube height perpendicular to centerline at piezometer taps is 10.328 in. Draft tube width is 29.506 in. There are two piers with a total width of 6.557 in. Total flow passage width is 22.949 in. Total flow area is 237.02 $in^2$, or 1.646 $ft^2$.

### Turbine Dimensions

| | | |
|---|---|---|
| Runner Inlet ($D_1$) | 10.415 in diameter | 0.868 ft diameter |
| Runner Throat ($D_2$) | 8.856 in diameter | 0.738 ft diameter |
| Runner Exit | 9.409 in diameter | 0.784 ft diameter |
| Draft Tube Inlet ($D_3$) | 9.465 in diameter | 0.788 ft diameter |

### Venturi Meter

$D_1$ = 17.297 in
$D_2$ = 8.949 in
$C_d$ = 0.98547
$A$ = 0.4368 $ft^2$

$$Q = \frac{C_d A \sqrt{2g\Delta H}}{\sqrt{1-\left(\frac{D_2}{D_1}\right)^4}}$$

### Torque and Speed Measurements

The Daytronic torque load cell located on the dynamometer carcass is on a 24-in. lever arm. The torque can be computed from the DC voltage measured at the dynamometer control cabinet as:

$$T_{ft\cdot lb}=93738(DCV)-10.92$$

The shaft speed may be computed from the DC voltage output by the Servotek tachometer generator as:

$$N_{RPM}=142.86(DCV)$$

Wicket Gate Calibration

Table F.1. - Wicket gate calibration (as determined after installation at CSU).

| Gate Opening (Degrees) | Counter Reading | Gate Opening (Degrees) | Counter Reading |
|---|---|---|---|
| 6.2 | 99912 | 21.2 | 99655 |
| 7.2 | 99895 | 22.2 | 99636 |
| 8.2 | 99877 | 23.2 | 99619 |
| 9.2 | 99860 | 24.2 | 99601 |
| 10.2 | 99844 | 25.2 | 99583 |
| 11.2 | 99826 | 26.2 | 99564 |
| 12.2 | 99810 | 27.2 | 99547 |
| 13.2 | 99794 | 28.2 | 99528 |
| 14.2 | 99776 | 29.2 | 99511 |
| 15.2 | 99760 | 30.2 | 99494 |
| 16.2 | 99744 | 31.2 | 99477 |
| 17.2 | 99725 | 32.2 | 99460 |
| 18.2 | 99708 | 33.2 | 99444 |
| 19.2 | 99690 | 34.2 | 99428 |
| 20.2 | 99673 | 35.2 | 99413 |
| | | 36.2 | 99399 |

Full gate opening in the prototype is 34°.

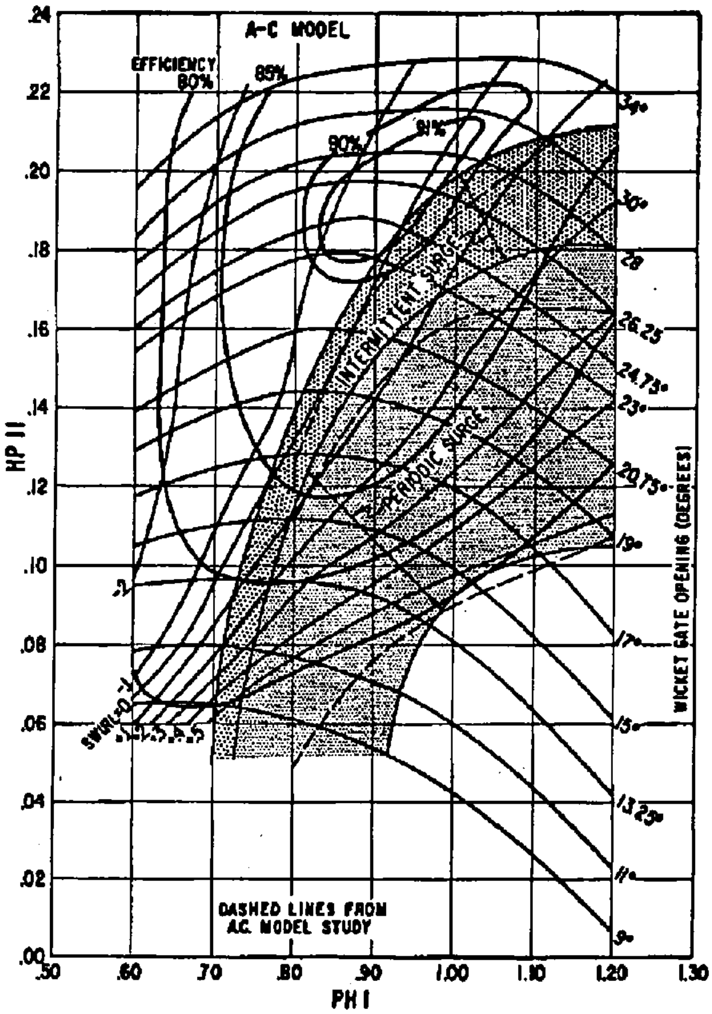
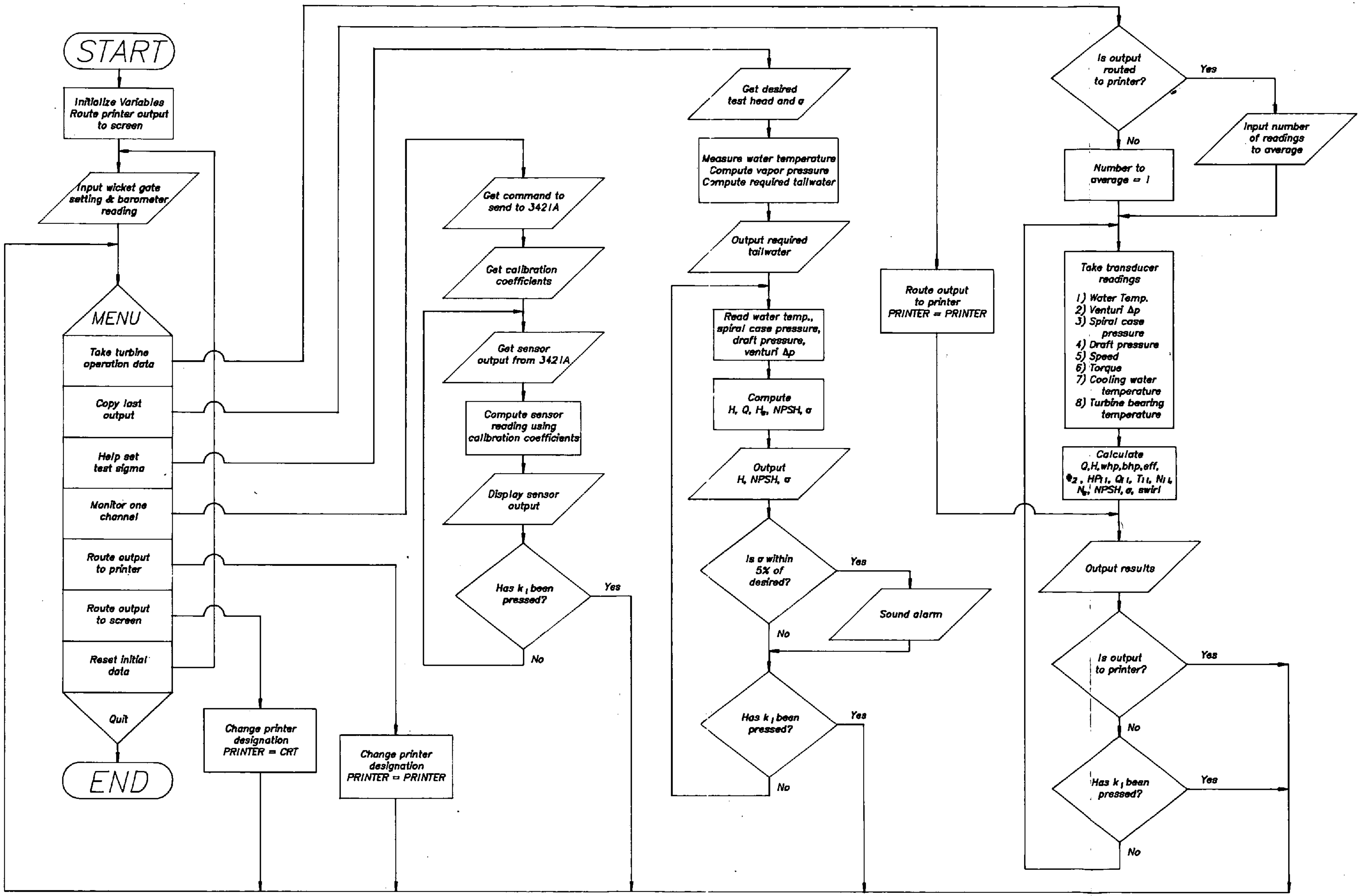



Figure F-1. - Allis Chalmers 9-in model efficiency-hill curve, as determined from tests conducted with the model installed at Estes Powerplant.

## APPENDIX G

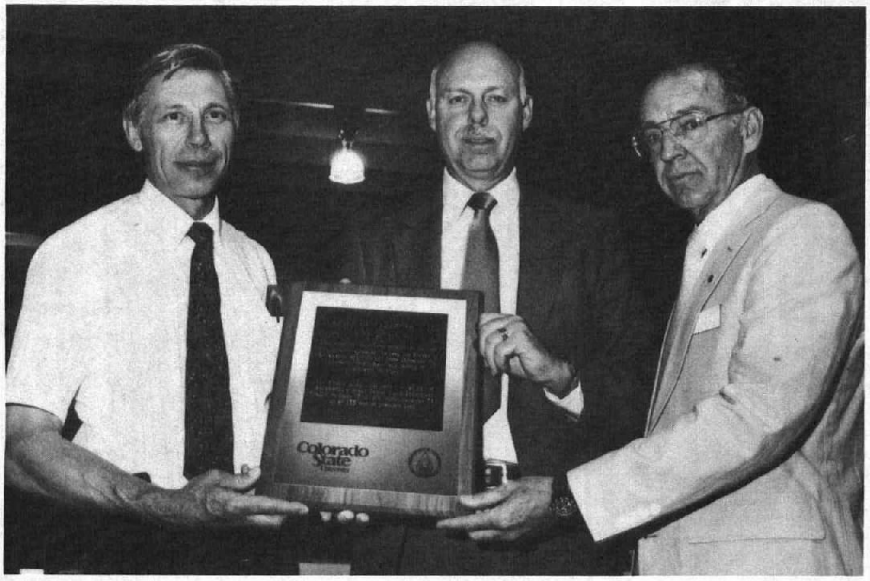
### Data Acquisition Program

# DATA ACQUISITION PROGRAM

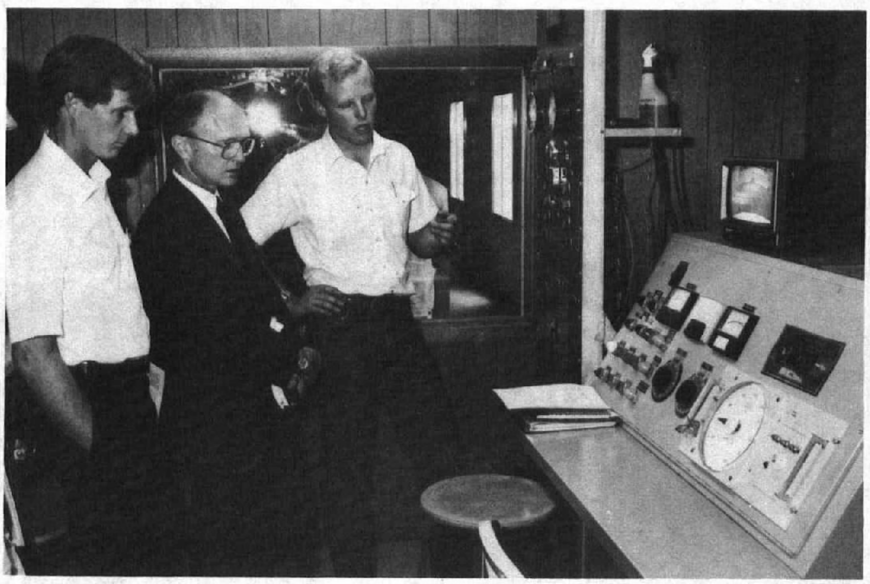


# APPENDIX H

## Turbine Research Facility Dedication




From left, Dr. James F. Ruff, Hydraulics Program Leader; Raymond H. Willms, Project Manager, Eastern Colorado Projects Office, Reclamation; and Dr. Morris M. Skinner, Turbine Research Facility.



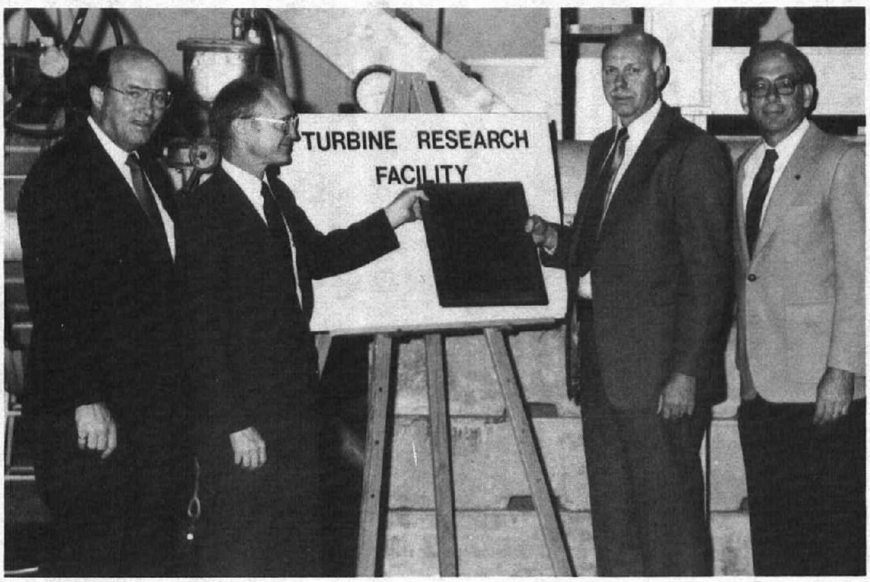
Control room during demonstration of model turbine operation.

From right: Tony Wahl, CSU Hydraulics Program; Dr. Ralph E. Smith, Associate Vice President for Research; and Dave Rogers, Reclamation.

Dedication ceremonies, June 29, 1989

Speaker: Dr. Frederick W. Smith, Associate Dean for Research

Seated from left: Dr. John D. Nelson, Civil Engineering Department Head; Philip H. Burgi, Chief, Hydraulics Branch, Reclamation; Dr. James F. Ruff, Hydraulics Program Leader; Dr. Morris M. Skinner, Turbine Research Facility; Raymond H. Willms, Project Manager, Eastern Colorado Projects Office, Reclamation; Dr. Ralph E. Smith, Associate Vice President for Research; and Dr. Francis A. Kulacki, Dean of Engineering.




Installation of the dedication plaque.

From left, Dr. John D. Nelson, Department Head; Dr. Ralph E. Smith, Associate Vice President for Research; Raymond H. Willms, Project Manager, Eastern Colorado Projects Office, Reclamation; and Philip H. Burgi, Chief, Hydraulics Branch, Reclamation .



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## Mission of the Bureau of Reclamation

*The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.*

*The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.*

*Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.*

CHIEF HYDRAULICS BRANCH
CODE D-3750 TPB