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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

- - -

TECHNICAL MEMORANDUM NO. 631

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TESTS ON HYDRAULIC GOVERNORS AT GREEN MOUNTAIN POWERPLANT COLORADO-BIG THOMPSON PROJECT

- - -

By
John Parmakian

- - -

Denver, Colorado
July 11, 1946

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DEPARTMENT OF THE INTERIOR

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MEMORANDUM TO CHIEF ~~DESIGNING~~ ENGINEER

SUBJECT: TESTS ON HYDRAULIC GOVERNORS AT

GREEN MOUNTAIN POWERPLANT

COLORADO-BIG THOMPSON PROJECT

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BY JOHN PARMAKIAN

\- - -

Under direction of

R. E. GLOVER

\- - -

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(Price $1.25)

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INTRODUCTION

On April 23, 1946, nine tests were conducted on the hydraulic governor of Unit No. 2 at Green Mountain Powerplant, the general arrangement of which is shown in Figure 1. In tests 1 to 6, various loads were rejected by circuit breaker shutdown, solenoid shutdown, and manual shutdown. In tests 7 to 9, different settings of the dashpot by-pass needle valve were used while the turbine was running at synchronous speed at the no-load gate position. During all of the nine tests a simultaneous time record was taken of the movement of various parts of the governor and the pressure and speed changes at the turbine.

The purpose of these tests was to ascertain the waterhammer pressure and speed changes due to changes in load at the turbine. This information is of value in the design of future penstocks.

DESCRIPTION OF GOVERNOR OPERATION

A diagrammatic arrangement of the various parts of the Woodward Governor tested, is shown in Figure 2.

(1) For normal operation:

The governor head is driven by a synchronous motor at a definite speed ratio to the turbine speed. An increase in turbine speed will move the flyballs outward and cause the speeder rod to move downward. The speeder rod connects through two sets of levers to the pilot valve and will move the pilot valve plunger down. The movement of the pilot valve and the subsequent flow of oil to the relay valve control plunger will move the relay valve down. The flow of oil into the servomotor cylinder will then move the servomotor piston and cause the gates to move

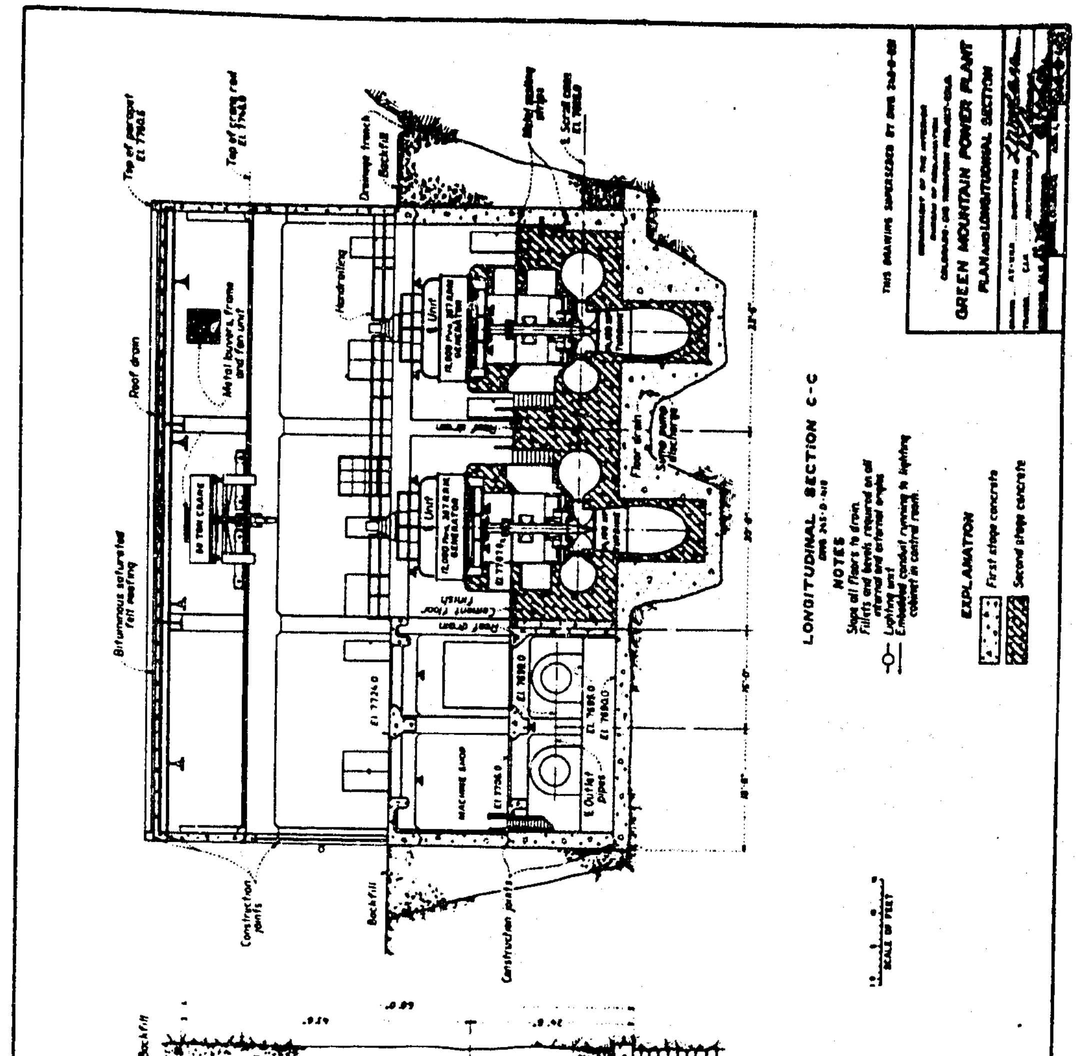

LONGITUDINAL SECTION C-C
NOTES
EXPLANATION
First stage concrete
Second stage concrete
PLAN THRU ℄ OF TURBINES AND THRU ℄ OF NEEDLE VALVES
GREEN MOUNTAIN POWER PLANT
Bituminous saturated felt roofing
Construction joints
Backfill
Machine shop
Cork joint
Metal sealing strips
Septic tanks

FIGURE 1

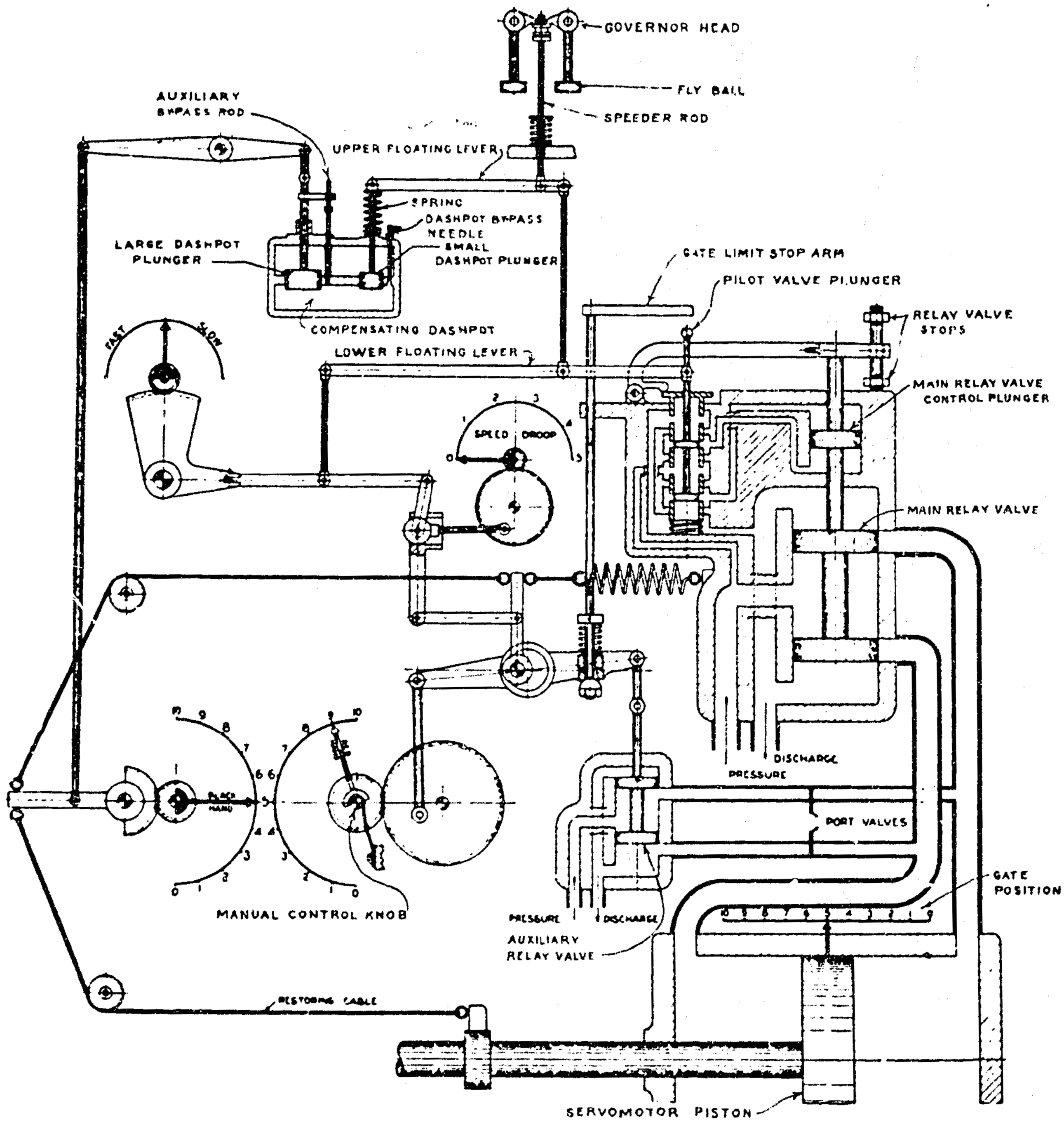

GOVERNOR HEAD
FLY BALL
SPEEDER ROD
AUXILIARY BYPASS ROD
UPPER FLOATING LEVER
SPRING
DASHPOT BYPASS NEEDLE
SMALL DASHPOT PLUNGER
LARGE DASHPOT PLUNGER
COMPENSATING DASHPOT
GATE LIMIT STOP ARM
PILOT VALVE PLUNGER
RELAY VALVE STOPS
FAST
SLOW
LOWER FLOATING LEVER
MAIN RELAY VALVE CONTROL PLUNGER
SPEED DROOP
MAIN RELAY VALVE
DISCHARGE
PRESSURE
PORT VALVES
GATE POSITION
MANUAL CONTROL KNOB
PRESSURE
DISCHARGE
AUXILIARY RELAY VALVE
RESTORING CABLE
SERVOMOTOR PISTON

FIGURE 2

in the closing direction in order to return the speed to normal. As the servomotor closes the gates, the large dashpot plunger moves up a proportional distance since it is connected to the servomotor piston through the restoring cable. For each movement of the large dashpot plunger the small plunger is moved a proportional amount in the opposite direction. If the bypass is set properly, the small dashpot plunger acting on the upper floating lever will recenter the pilot valve just as the gates reach the proper position. The dashpot bypass will then permit the small dashpot plunger to return to its normal central position in unison with the return of the flyballs to their normal position.

(2) For manual shutdown through the main relay valve:

In order to manually close the gates by means of the main relay valve, the transfer valve must first be set for manual control of the main relay valve. Turning the gate limit knob counterclockwise will then close the gate to any desired setting. The rotation of the gate limit knob acts through links and levers to the gate limit stop arm which acts on the top of the pilot valve plunger. This will force the pilot valve plunger down and will cause the relay valve to move down which will start the gates to close.

(3) For solenoid shutdown of the turbine gates:

Turbine shutdown with the solenoid can be accomplished either manually with the solenoid switch or automatically through the safety overspeed shutdown device. When the solenoid is tripped, the safety latch is released and the movement is transferred through levers to force the pilot valve down. This movement will move the main relay down and start the gates to close.

DESCRIPTION OF GOVERNOR TESTS

Table 1 shows the conditions existing at Unit No. 2 for the nine tests:

Table 1

Test No.	Load rejected	Gate position at load rejection	Method of load rejection	Dashpot auxilary bypass operative	Position of dashpot needle valve bypass
1	6,000 kw	0.450	Circuit-breaker shutdown	Yes	5/8 turn open
2	6,000 kw	0.450	Circuit-breaker shutdown	No	5/8 turn open
3	6,000 kw	0.450	Solenoid shutdown	No	5/8 turn open
4	6,000 kw	0.445	Manual shutdown	No	5/8 turn open
5	11,400 kw	1.000	Circuit-breaker shutdown	No	5/8 turn open
6	3,000 kw	0.270	Circuit-breaker shutdown	No	5/8 turn open
7	- - - - -	0.045*	- - - - - - - - - - - - - -	No	5/8 turn open
8	- - - - -	0.045*	- - - - - - - - - - - - - -	Yes	5/8 turn open
9	- - - - -	0.045*	- - - - - - - - - - - - - -	Yes	1/8 turn open

*No load gate position

During these tests a simultaneous time record was taken of the following:

(a) Movement of the speeder rod.

(b) Movement of the pilot valve plunger.

(c) Movement of the main-relay valve plunger.

(d) Movement of the large plunger in the compensating dashpot.

(e) Movement of the small plunger in the compensating dashpot.

(f) Turbine gate position.

(g) Penstock pressure at the turbine gates.

(h) Generator voltage wave at Unit No. 2 (Changes in turbine speed were taken from this record)

(i) Generator current wave at Unit No. 2.

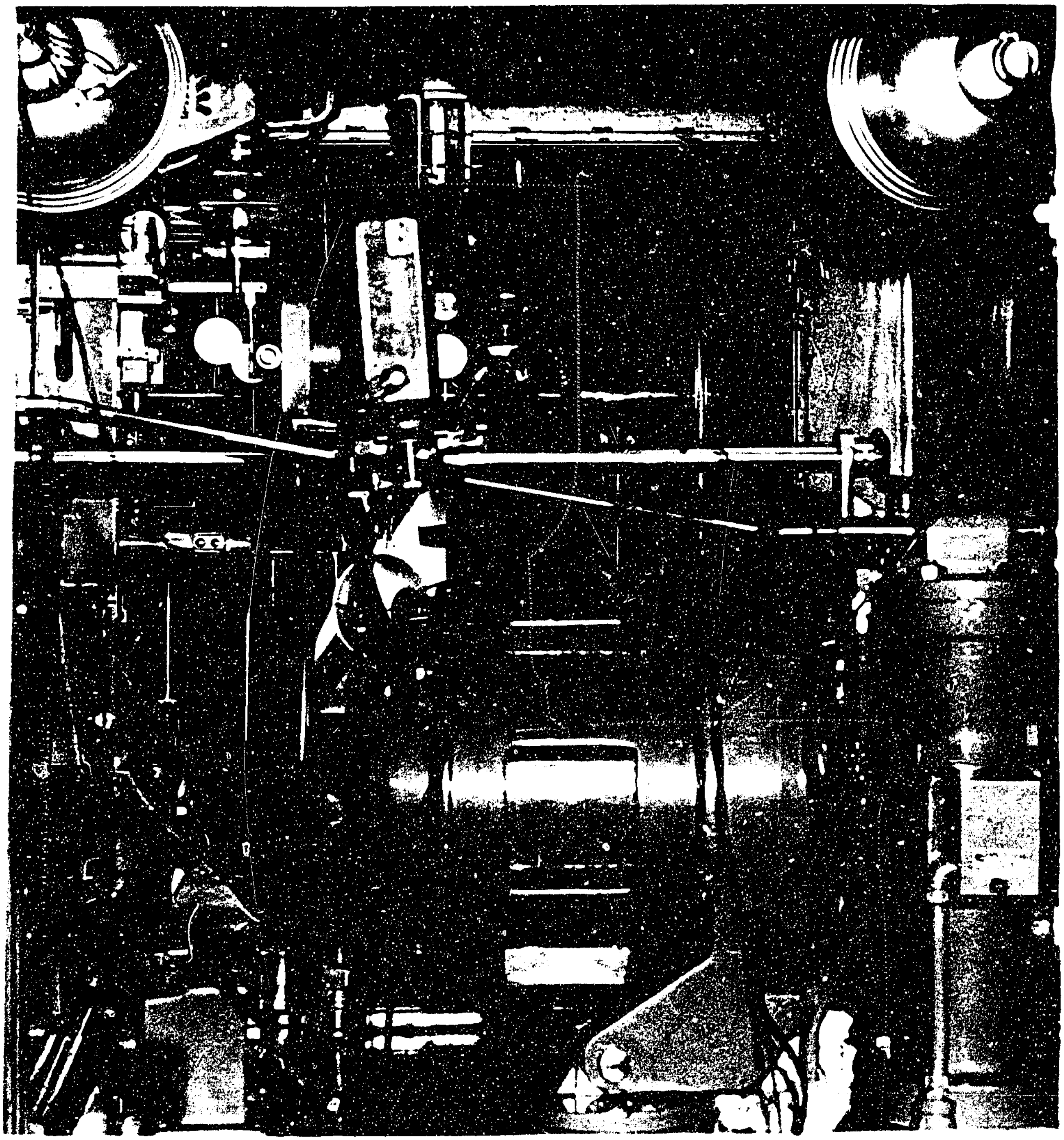
(j) Voltage wave of outside transmission line.

DESCRIPTION OF TEST EQUIPMENT

The time history of the movement of the various parts of the governor was obtained by mounting dial gages at appropriate points on the governor and photographing the motion of the dials by means of three motion picture cameras as shown in Figure 3. The movement of the turbine gates was obtained with an additional motion picture camera by photographing the gate position indicator which is located on the front panel of the governor cabinet. Synchronization of all motion picture records was accomplished by photographing stop watches in the field of view of each camera and also by photographing the lighting of a signal light at the start of each test.

The time history of penstocks pressures was measured by means of a special pressure cell which was designed to record on an element of an oscillograph. The pressure cell had been previously calibrated for 200 and 250 feet of water by means of a mercury column which is located in the powerplant.

The time history of the voltage wave and current wave at Unit No. 2 and the voltage wave of the outside line were measured by means of separate elements on the oscillograph. The time history of the speed changes of Unit No. 2 was obtained by computation from the voltage-wave record.



View of interior of governor cabinet during test of Unit No. 2,
Green Mountain Power Plant.

FIGURE 3

RESULTS BASED ON GOVERNOR TESTS

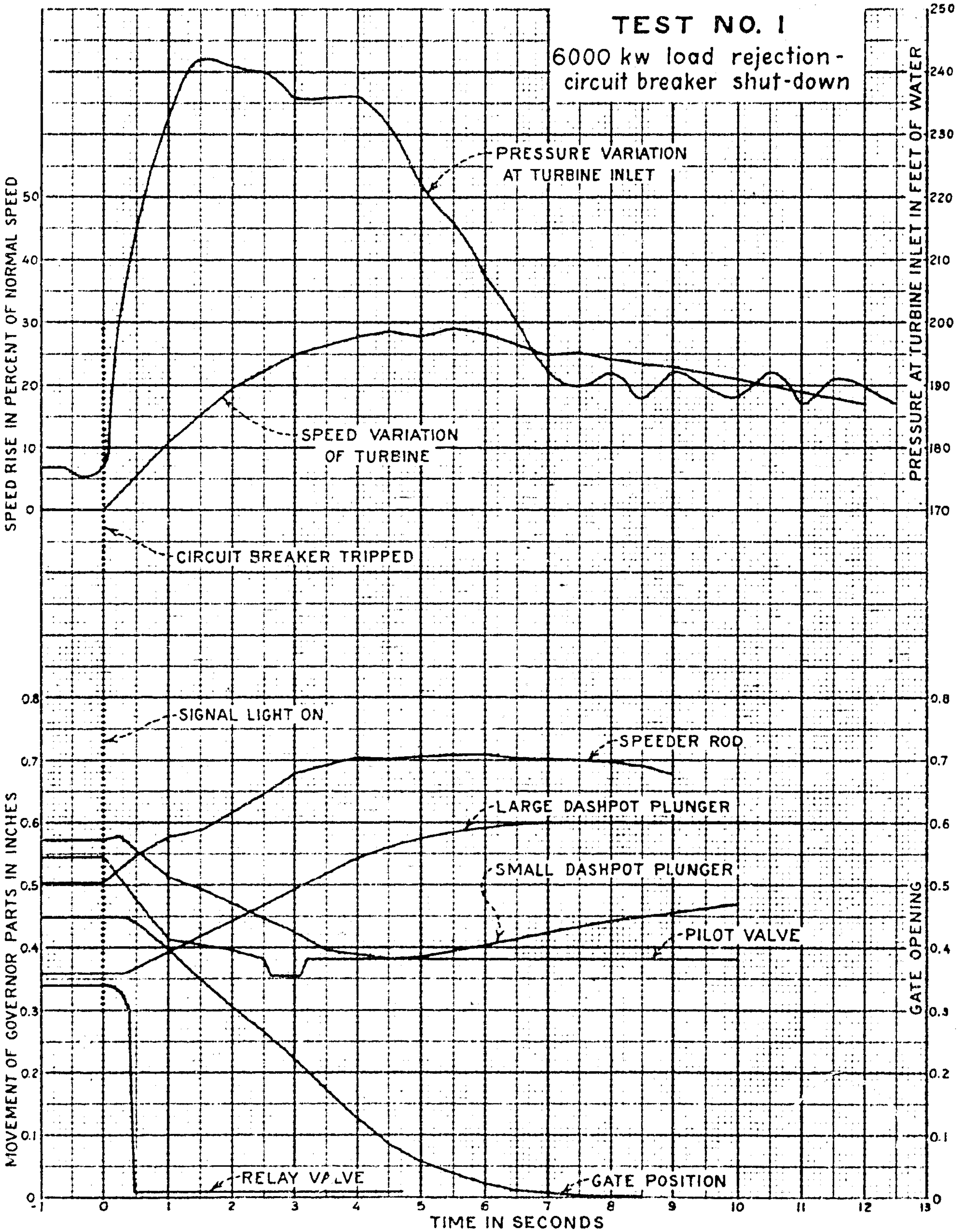
The time history of the movement of the various parts of the governor, turbine gates and the pressure and speed changes at the turbine are shown in Figures 4 to 11 for tests 1 to 8, inclusive. For the no-load condition of tests 7 and 8 with the dashpot needle-valve bypass, 5/8 turn open, the governor hunting was severe. For the no-load condition of test 9, with the dashpot needle-valve bypass 1/8 turn open, the gate position remained steady at 0.045 gate and there was no appreciable movement of the pilot valve, relay valve, dashpot plungers, or change in turbine speed or penstock pressure. The governor hunting condition with the dashpot needle-valve bypass 5/8 turn open does not represent a malfunction of the governor but is a normal condition which can occur whenever the dashpot compensation is reduced too much.

DRAFT-TUBE SURGE TESTS

After the completion of the tests described above, a series of tests were conducted to measure the magnitude and frequency of draft-tube surges at various gate openings. For these tests a time history of the pressure changes immediately below the turbine runner was measured by means of an element of the oscillograph and the pressure cell which had been modified to give greater sensitivity. Simultaneously a time record of the current and voltage at Unit No. 2 was also recorded on separate elements of the oscillograph. The conclusions based on the results of these tests are included in the following paragraph.

CONCLUSIONS

The following conclusions may be reached as a result of these tests:



TEST NO. 1
6000 kw load rejection - circuit breaker shut-down
PRESSURE VARIATION AT TURBINE INLET
SPEED VARIATION OF TURBINE
CIRCUIT BREAKER TRIPPED
SIGNAL LIGHT ON
SPEEDER ROD
LARGE DASHPOT PLUNGER
SMALL DASHPOT PLUNGER
PILOT VALVE
RELAY VALVE
GATE POSITION
SPEED RISE IN PERCENT OF NORMAL SPEED
PRESSURE AT TURBINE INLET IN FEET OF WATER
MOVEMENT OF GOVERNOR PARTS IN INCHES
GATE OPENING
TIME IN SECONDS

FIGURE 4

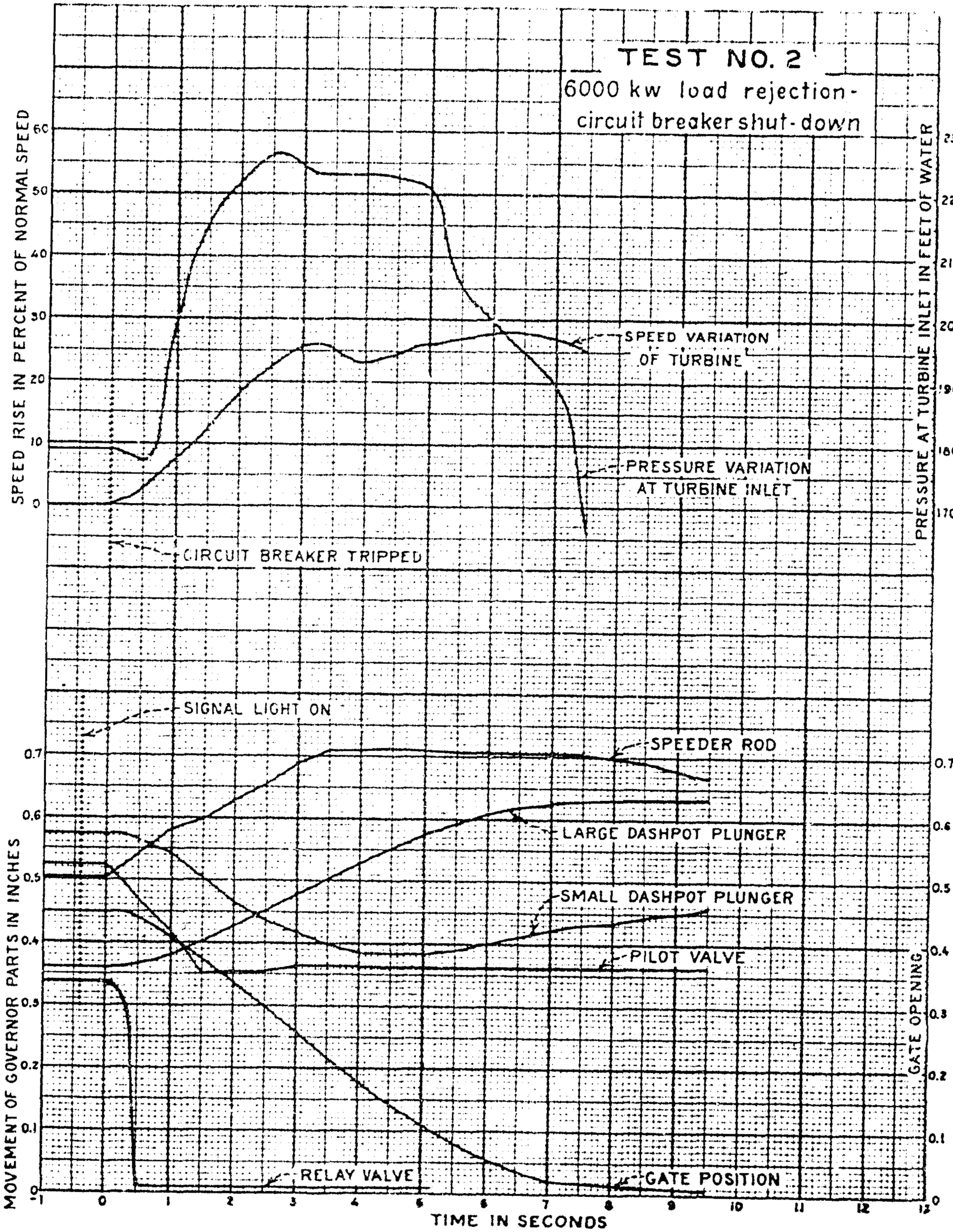

TEST NO. 2
6000 kw load rejection-
circuit breaker shut-down
SPEED RISE IN PERCENT OF NORMAL SPEED
PRESSURE AT TURBINE INLET IN FEET OF WATER
SPEED VARIATION
OF TURBINE
PRESSURE VARIATION
AT TURBINE INLET
CIRCUIT BREAKER TRIPPED
SIGNAL LIGHT ON
SPEEDER ROD
LARGE DASHPOT PLUNGER
SMALL DASHPOT PLUNGER
PILOT VALVE
RELAY VALVE
GATE POSITION
MOVEMENT OF GOVERNOR PARTS IN INCHES
GATE OPENING
TIME IN SECONDS

FIGURE 5

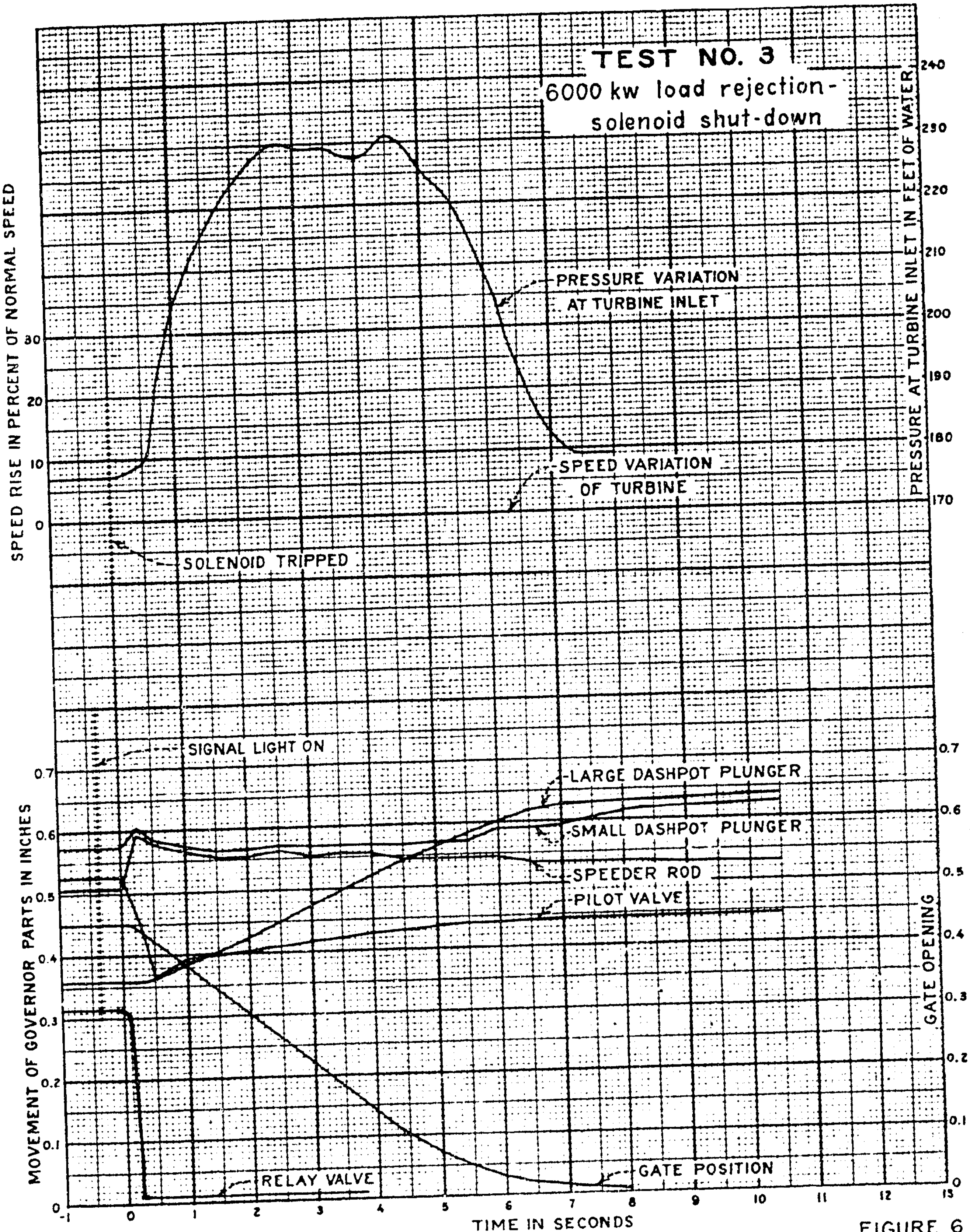

TEST NO. 3
6000 kw load rejection-
solenoid shut-down
PRESSURE VARIATION
AT TURBINE INLET
SPEED VARIATION
OF TURBINE
SOLENOID TRIPPED
SPEED RISE IN PERCENT OF NORMAL SPEED
PRESSURE AT TURBINE INLET IN FEET OF WATER
SIGNAL LIGHT ON
LARGE DASHPOT PLUNGER
SMALL DASHPOT PLUNGER
SPEEDER ROD
PILOT VALVE
RELAY VALVE
GATE POSITION
MOVEMENT OF GOVERNOR PARTS IN INCHES
GATE OPENING
TIME IN SECONDS

FIGURE 6

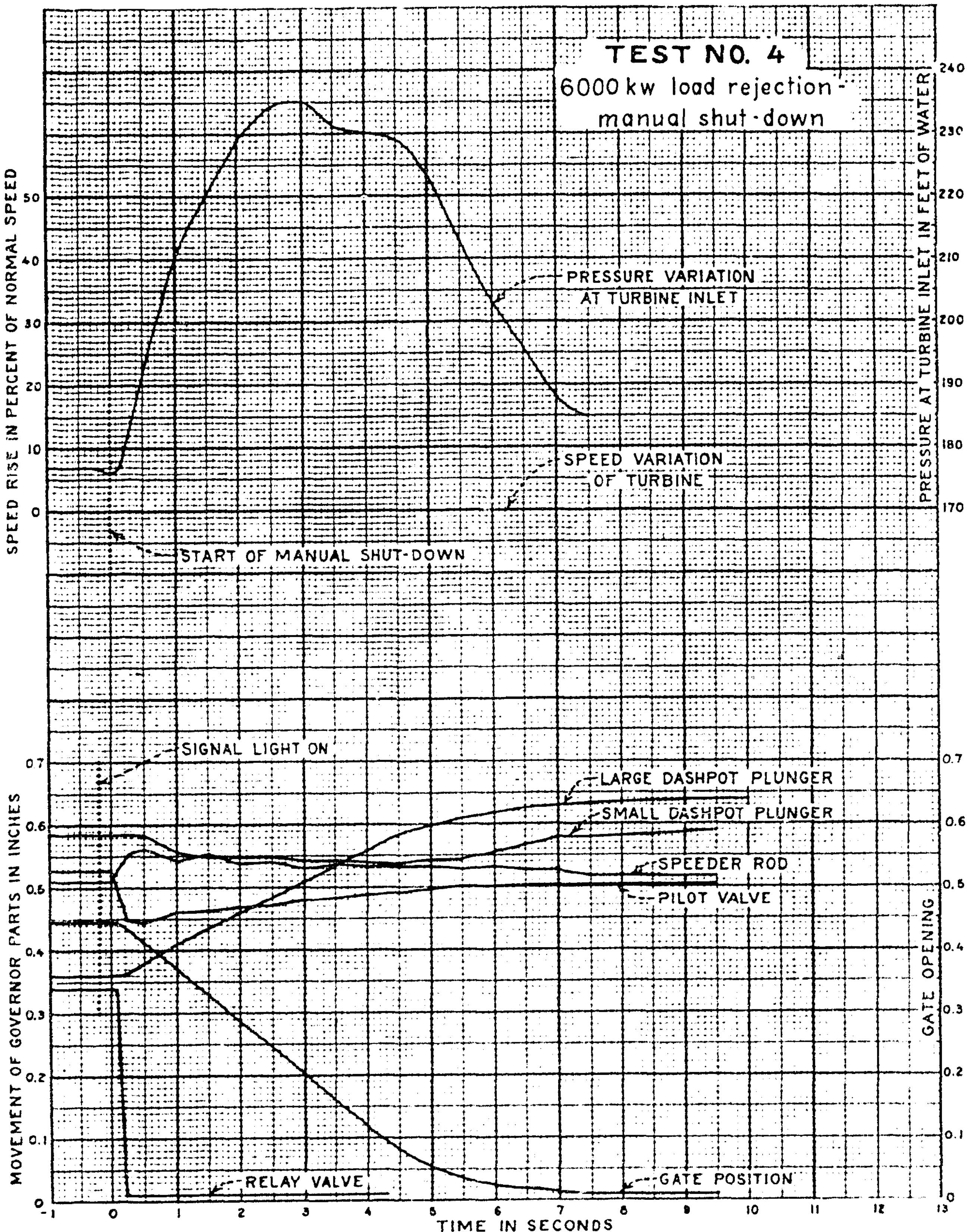

TEST NO. 4
6000 kw load rejection - manual shut-down
SPEED RISE IN PERCENT OF NORMAL SPEED
PRESSURE AT TURBINE INLET IN FEET OF WATER
PRESSURE VARIATION AT TURBINE INLET
SPEED VARIATION OF TURBINE
START OF MANUAL SHUT-DOWN
SIGNAL LIGHT ON
LARGE DASHPOT PLUNGER
SMALL DASHPOT PLUNGER
SPEEDER ROD
PILOT VALVE
MOVEMENT OF GOVERNOR PARTS IN INCHES
GATE OPENING
RELAY VALVE
GATE POSITION
TIME IN SECONDS

FIGURE 7

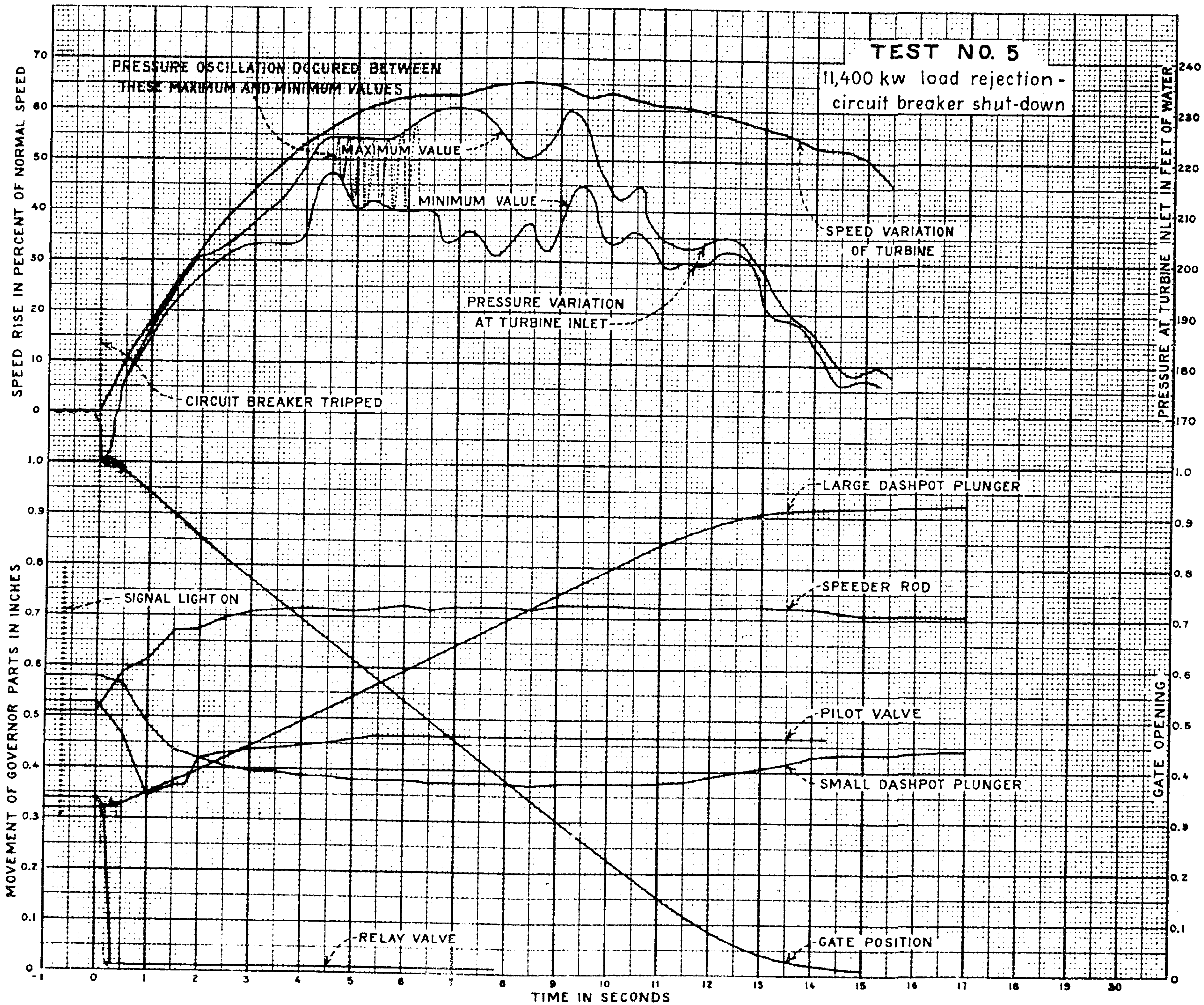

TEST NO. 5
11,400 kw load rejection - circuit breaker shut-down
PRESSURE OSCILLATION OCCURED BETWEEN THESE MAXIMUM AND MINIMUM VALUES
MAXIMUM VALUE
MINIMUM VALUE
SPEED VARIATION OF TURBINE
PRESSURE VARIATION AT TURBINE INLET
CIRCUIT BREAKER TRIPPED
LARGE DASHPOT PLUNGER
SIGNAL LIGHT ON
SPEEDER ROD
PILOT VALVE
SMALL DASHPOT PLUNGER
RELAY VALVE
GATE POSITION
SPEED RISE IN PERCENT OF NORMAL SPEED
PRESSURE AT TURBINE INLET IN FEET OF WATER
MOVEMENT OF GOVERNOR PARTS IN INCHES
GATE OPENING
TIME IN SECONDS

FIGURE 8

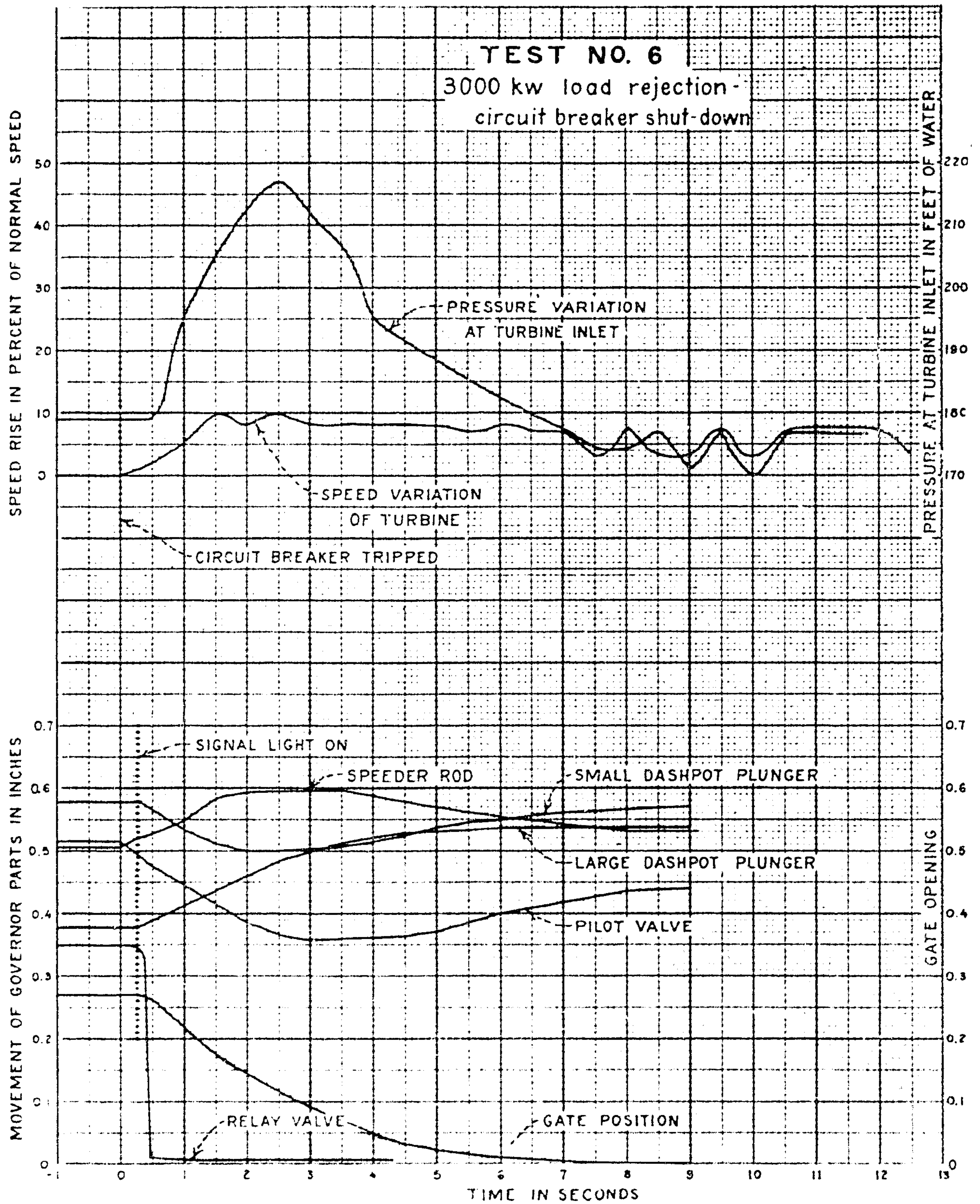
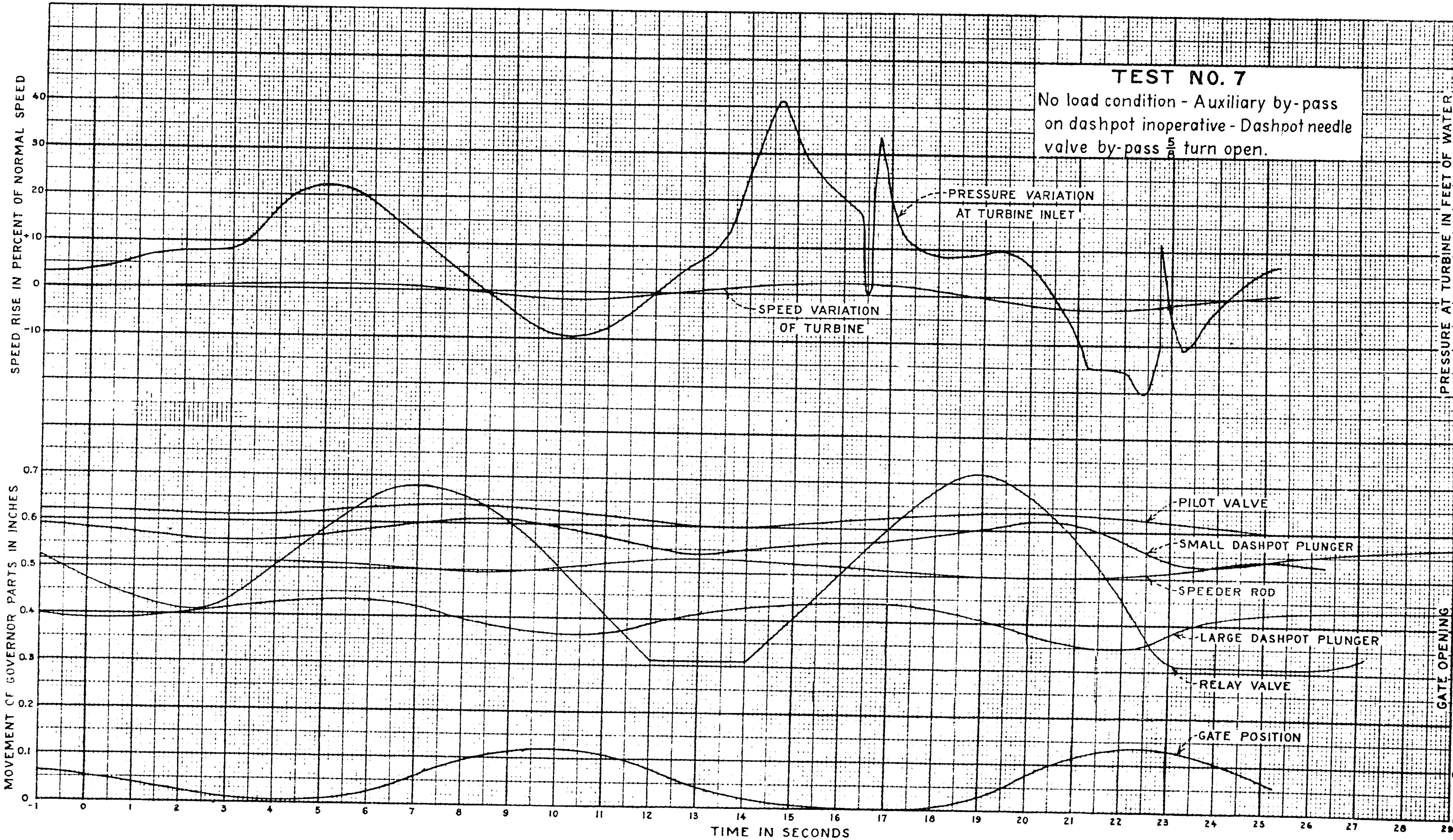

TEST NO. 6
3000 kw load rejection - circuit breaker shut-down
SPEED RISE IN PERCENT OF NORMAL SPEED
PRESSURE AT TURBINE INLET IN FEET OF WATER
PRESSURE VARIATION AT TURBINE INLET
SPEED VARIATION OF TURBINE
CIRCUIT BREAKER TRIPPED
MOVEMENT OF GOVERNOR PARTS IN INCHES
GATE OPENING
SIGNAL LIGHT ON
SPEEDER ROD
SMALL DASHPOT PLUNGER
LARGE DASHPOT PLUNGER
PILOT VALVE
RELAY VALVE
GATE POSITION
TIME IN SECONDS

FIGURE 9



TEST NO. 7
No load condition - Auxiliary by-pass on dashpot inoperative - Dashpot needle valve by-pass $\frac{5}{8}$ turn open.
PRESSURE VARIATION AT TURBINE INLET
SPEED VARIATION OF TURBINE
SPEED RISE IN PERCENT OF NORMAL SPEED
PRESSURE AT TURBINE IN FEET OF WATER
PILOT VALVE
SMALL DASHPOT PLUNGER
SPEEDER ROD
LARGE DASHPOT PLUNGER
RELAY VALVE
GATE POSITION
MOVEMENT OF GOVERNOR PARTS IN INCHES
GATE OPENING
TIME IN SECONDS

FIGURE 10

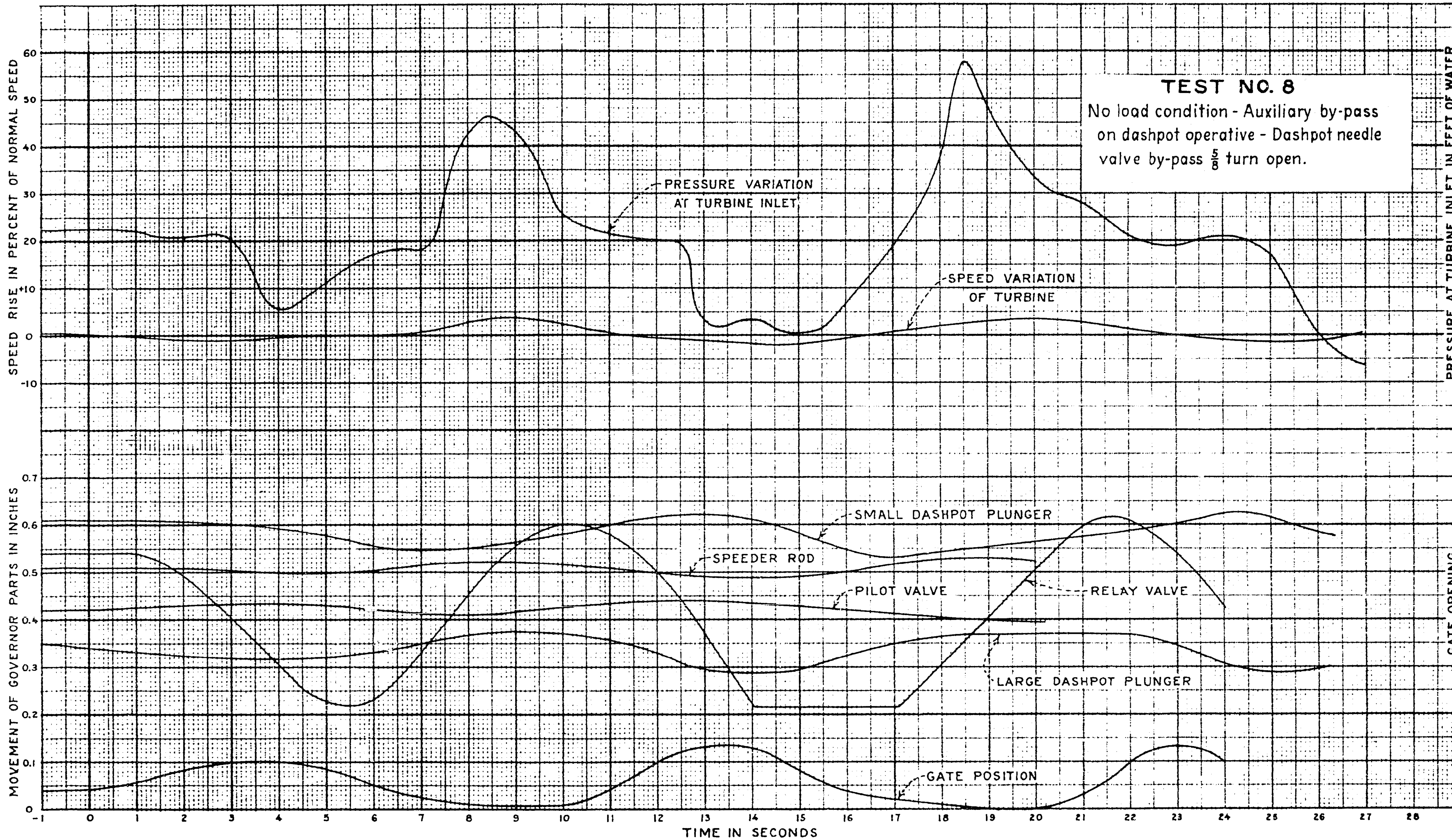

TEST NO. 8
No load condition - Auxiliary by-pass on dashpot operative - Dashpot needle valve by-pass 5/8 turn open.
PRESSURE VARIATION AT TURBINE INLET
SPEED VARIATION OF TURBINE
SMALL DASHPOT PLUNGER
SPEEDER ROD
PILOT VALVE
RELAY VALVE
LARGE DASHPOT PLUNGER
GATE POSITION
SPEED RISE IN PERCENT OF NORMAL SPEED
PRESSURE AT TURBINE INLET IN FEET OF WATER
MOVEMENT OF GOVERNOR PARTS IN INCHES
GATE OPENING
TIME IN SECONDS

FIGURE 11

(a) Essentially linear gate closures can be obtained from any gate position.

(b) The sensitivity of the flyball governor head is such that the main relay valve is opened wide for sudden load changes of one-fourth full load or less.

(c) The windage, friction, and open-circuit core losses in the unit tested are estimated at 425 kilowatts at the normal speed of 257 rpm.

(d) The estimated time for a unit to coast to a stop from normal speed of 257 rpm is 6 minutes.

(e) The increase in pressure due to waterhammer caused by governor hunting is 30 feet of water when the turbine is operating under a gross head of 197.3 feet.

(f) The draft tube surge amplitude at 0.49 gate varies from minus 12.3 feet to plus 9.3 feet. This gate opening gave the maximum power swings.

(g) The draft-tube surge frequency at 0.49 gate is about 64 cycles per minute.

(h) The excess pressures and speed rise caused by the rejection of various loads are as follows:

Table II

Load rejected	Maximum measured pressure at turbine including waterhammer	Maximum computed pressure based on linear gate closure	Computed increase in pressure due to waterhammer	Maximum measured speed rise in percent of normal speed
3,000 kw	217 feet	223 feet	34 feet	10
6,000 kw (2 tests)	226,242 feet	230 feet	41 feet	28, 29
6,000 kw (solenoid shutdown)	231 feet	233 feet	44 feet	0*
6,000 kw (manual shutdown)	235 feet	235 feet	46 feet	0*
11,500 kw	230 feet	232 feet	43 feet	65

*No speed rise for these tests as the unit remained in synchronism with the rest of the system.

(i) The voltage rise at Unit No. 2 upon the rejection of full load is 16.3 percent of the normal generator voltage.

(j) For small load changes such as occur under normal operation the relay valve makes only small movements from its normal position midway between the stops and the governor operates in precisely the same way as it would if the relay valve stops were removed. There would, therefore, be no gain in governor ability under normal conditions if the stops were reset to permit faster operation under abnormal or emergency conditions of load additions or rejections.

BASIC DATA

Length of 16-foot 0-inch diameter concrete lined tunnel = 151 feet.

Length of 18-foot 0-inch diameter concrete lined tunnel = 569 feet.

Length of 102-inch diameter steel penstock = 844 feet.

Length of 84-inch diameter steel penstock = 49 feet.

Wave travel time (L/a) = 0.452 seconds.

Reservoir elevation during tests = 7886.9 feet.

Tailwater surface elevation during tests = 7689.6 feet.

Gross head on the turbine = 197.3 feet.

Number of generating units in powerplant, 2.

Speed of generator turbine unit = 257 rpm.

Normal generator voltage = 6,900 volts.

WR^2 of generator = 2,000,000 lb. ft.^{2}.

WR^2 of turbine = 80,000 lb. ft.^{2}.

Governor set for closure from full gate to zero gate in 13 seconds during tests.

Generator rated at 12,000 kva.

Generator manufacturer - Allis Chalmers Corporation.

Turbine rated at 15,000 hp, for net head of 185 feet.

Turbine manufacturer - Newport News Shipbuilding and Dry Dock Company.

Hydraulic turbine data is shown in Figure 12.

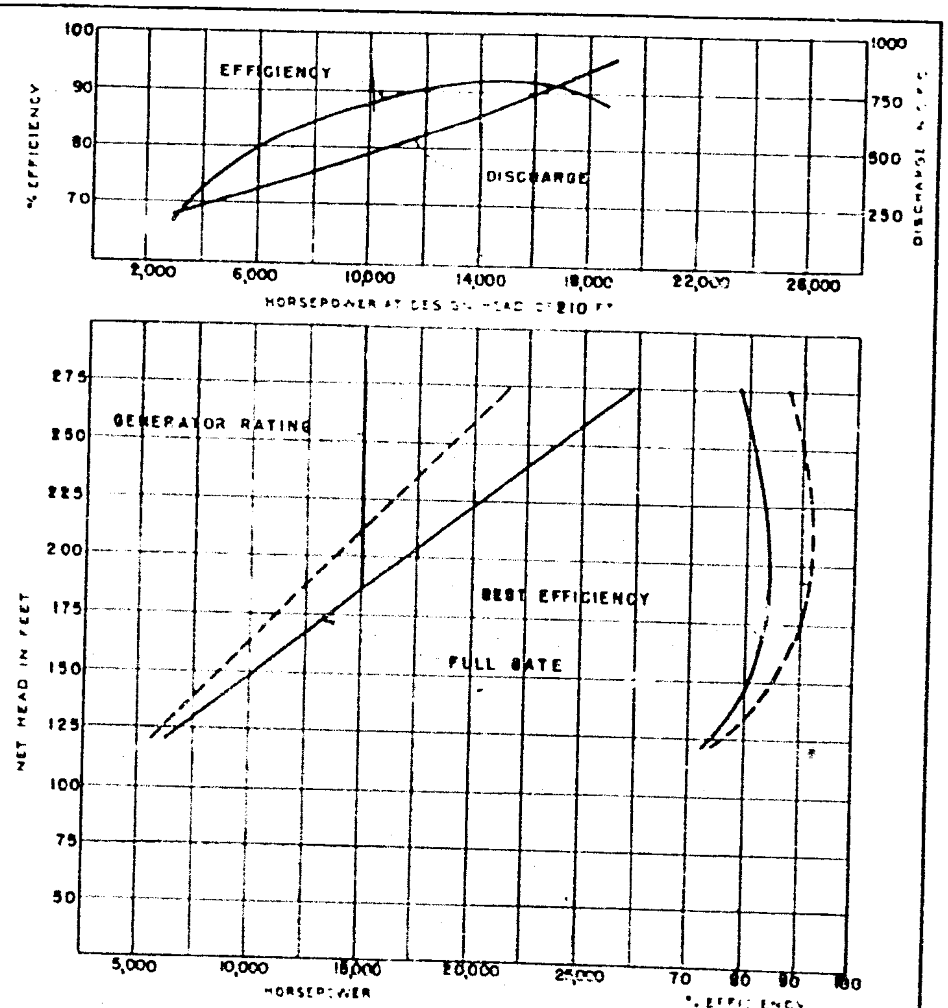
Governor manufacturer - Woodward Governor Company.

Governor designed for maximum rate of closure from full gate to zero gate in 4 seconds.

ACKNOWLEDGMENT

The following personnel assisted in the conduct of these tests: Charles W. Thomas and Robert H. Keummich of the Engineering and Geological Control and Research Division, Frank W. Taylor of the Technical Engineering Analysis Section, General Engineering Division, and John M. Eyer of Regional Office No. 7.

GREEN MOUNTAIN POWER PLANT ..... **COLORADO BIG THOMPSON** .... PROJECT.
SPECIFICATIONS NO. **802** .... UNITS **1 AND 2** .... DATE **OCTOBER 1938**
TURBINE RATING IN H.P. **15,000** .... RATED HEAD **185** FT. SPEED **257** R.P.M.
Generator rating in kv-a. **12,000** .... Power factor **90** ... percent.
Turbine mfgr. **NEWPORT NEWS SHPBLDG AND D.D. CO.** Type **FRANCIS**
Cost per unit f.o.b. factory **$49,900** .... Weight **160,000** ...... lbs
Cost per h.p. **$3.26** .... Weight per h.p. **10.67** ...... lbs
Type of scroll case ... **RIVETED PLATE STEEL SPIRAL**
Type of draft tube **ELBOW WITH PLATE STEEL LINER (ONE PIER)**
Weight of runner **12,000** lbs.
Weight of turbine parts including hydraulic thrust to be carried by generator thrust bearing **110,000** lbs
Governor capacity in foot-lbs. **65,000** .... Pipe size **3** ..... inches.
Gov. mfgr. **WOODWARD GOVERNOR CO.** .... Time element **4** ... seconds
Cost per unit f.o.b. factory **$12,000** .... Weight **14,500** ..... lbs
Generator mfgr. **ALLIS-CHALMERS MFG. CO.**
Generator WR^2 **2,000,000** .... lbs at one foot radius.
Turbine WR^2 **80,000** .... lbs at one foot radius.
Regulating constant of unit ($R.P.M.^2 \times WR^2 \div H.P.$) **9,180,000**
N_s of runner **38.4** ... at **210** ... foot head when delivering **15,000** ..... h.p. (Best eff.)
N_s of runner **43.8** ... at **210** ... foot head when delivering **19,800** ..... h.p. (Full gate)
H.P. at **210** ft. (Design head) **19,500** .... ; at **100.0** percent of design head
H.P. at **261** ft. (Max. head) **25,000** .... , at **124.3** percent of design head.
H.P. at **126** ft. (Min. head) **9,000** .... ; at **60.0** percent of design head
H.P. at best efficiency equals **81.0** .... percent of h.p. at full gate.
Discharge (full gate) at **185** ft. hd. **815** c.f.s., at **261** ft. hd. **1040** c.f.s., at **126** ft. hd. **630** c.f.s.
Runaway speed at .... ft. hd. .... r.p.m. equals .... percent of normal speed
Dimensions of turbine:
Unit spacing **81.0** ft. .... Dia. of shaft **16½** inches
Max. dia. of runner **6.75** ft. .... Dia. of cover plate **9.92** ft.
Dia. of gate circle **8.0** ft. .... Number of wicket gates **16**
Height of distributor case **1.47** ft. .... Number of stay vanes **8**
Dia. of scroll case inlet **7.0** ft. .... Dia. at top of draft tube **6.29** ft. = D_3
Outside radii of stay vanes **6.92** to **6.92** ft.
Distance from center line of distributor to top of draft tube **1.98** ft.
Depth of draft tube **15.02** ft. equals **239** percent of dia. D_3
Length of draft tube **24.0** ft. equals **382** percent of dia. D_3
Width of draft tube **26.0** ft. equals **413** percent of dia. D_3
Distance from center line of turbine to center line of scroll case inlet **9.32** ft.
Distance from center line of distributor to minimum tailwater elevation (One unit operating at full load) **8.0** ft.
Pressure regulator mfgr. .... Type .... Size .... inches.
Cost per unit f.o.b. factory .... Weight .... lbs
Remarks:
Placed in operation **1, MAY 18, 1943; 2, JUNE 1, 1943.**



PREDICTED CHARACTERISTIC CURVES
FROM MANUFACTURER'S DATA
CURVE NO. HE-4921

HYDRAULIC TURBINE DATA
GREEN MOUNTAIN POWER PLANT
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

FIGURE 12

Mr. W. E. Bumpus, General Foreman; Mr. Lynn, Chief Operator; Mr. Morgan, machinist and Mr. Handy, pipefitter at Green Mountain Powerplant also contributed valuable assistance in the conduct of the tests.

The following personnel from the Technical Engineering Analysis Section, General Engineering Division, assisted in the analysis of test data and computations: Robert E. Glover, M. F. Ward, W. C. Montgomery, R. Saxton, C. L. Conner, C. C. Crawford, and F. W. Taylor.