GOVERNOR CONTROL FOR BULB TYPE GENERATING UNITS

PROJECT REPORT

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by

Balbir Singh Sandhu

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BALBIR SINGH SANDHU

A practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

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ABSTRACT

This work is concerned with the problem of speed control and application of appropriate speed governing equipment for hydraulic turbine generators and with special application for bulb type turbine units. Field test results obtained during the adjustment of governor parameters and their effect on the speed control performance of bulb type units are reported.

ACKNOWLEDGEMENTS

The author is grateful to Professor M. Z. Tarnawecky for the guidance and encouragement provided by him during the preparation of this report. Gratitude is also expressed to Manitoba Hydro for the opportunity to work on Bulb type units.

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1. INTRODUCTION

1.1 General

The use of bulb type turbines and generators for low head water power resources has increased due to continuous development of designs for maximum output with minimum overall dimensions resulting in economic installations and because of increasing energy shortage in the future there will be significant increases in the installation of bulb type units with the development of tidal power and the remaining low head hydraulic power resources. Attempts to further reduce the unit size resulted in the development of a straight flow turbine with the generator mounted on the rim of the runner blade tips but this scheme has proved to be practical only for small units. The speed response characteristics of these installations are quite distinct and different from vertical type hydraulic units. This necessitates that certain modifications must be made to the speed control equipment commonly known as Governors.

Many excellent papers, 1, 3, 4, 5, 6, have been published which describe the methods for determination and adjustment of the governor settings for optimum performance of conventional vertical type units. Techniques for the adjustment of governors for bulb type turbine units and field test results are not available in the published literature.

Governors for bulb type units must be well understood and adjusted for proper operation in the power system. This project report deals with the problem of governor adjustment of bulb turbines and particularly with the subject of field tests necessary to determine the optimum governor settings, when the unit is:

(i) Running at speed no load
(ii) Supplying load to the system
(iii) Subjected to load rejection conditions

1.2 The Problem

This project report studies the area of speed control of bulb turbine generators and particularly the effect of various governor settings upon the speed control of the unit. The following topics are examined in detail.

i) Available types of governors and their characteristics.

ii) Speed control requirements for horizontal bulb type turbine generators compared to vertical type hydro units.

iii) Effect of governor gain adjustments on speed response of bulb type units for the following cases:

  a) Speed no load operation
  b) On line operation
  c) Operation following load rejection

iv) Determination of governor settings from field tests for optimum performance under all known operating conditions.

1.3 System Data and Facilities for Studies

The governor system data used in the study and described in this project report is that of Manitoba Hydro's Jenpeg Generating Station. The tests outlined in Section 1.2 were performed on Jenpeg units. The details of tests performed and the results obtained are presented in the following chapters.

2. OPERATION AND TYPES OF HYDRO GOVERNORS

2.1 General

The power system must be able to withstand the sudden shocks experienced by equipment outages and load changes and maintain system frequency within a narrow deadband. Under steady state system operation the frequency deviations should remain within ± 0.02 Hz. The equipment and factors which govern system frequency under normal and abnormal operating conditions must be well understood by Power Systems Engineers.

In case of small isolated systems the frequency control is directly dependent upon the response of the speed governing equipment whereas in large interconnected systems, an inherently unstable governor may be stabilized by the flow of synchronizing power from the network. The stability margin of the overall system will be reduced. The dynamic response of the system is generally a function of the transmission system, generator characteristics, speed governors, and the characteristics of the electrical load including the effect of voltage regulation. The governor parameters are determined by simulation studies, adjusted in the field and checked by tests to ensure governor response for stable operation of the power system. In addition the governor gains are selected and checked in the field to limit speed rise on load rejections and fast return to normal speed, while keeping pressure rise in the scroll case within design limits. Some of the most commonly used terms for the study of governor systems are defined in Appendix A.

2.2 Operation in a Power System

To understand the operation of governors[1] in a power system, it is necessary to understand the sequence in which load changes take place in the system. The sudden load increase is supplied by the system in the following order:

(i) The machine with the largest synchronizing power will develop the largest change in load and this will be modified somewhat by the transmission system to which the machine is connected.

(ii) Due to load increase the system speed deviates from 60 Hz and the machine having larger mechanical starting time (T_m) constant will pick up the largest portion of total load change.

(iii) As system speed is changing, the most sensitive and responsive speed governor adjusts the power output of its unit in a direction to bring the frequency to 60 Hz.

(iv) Automatic generation control begins to redistribute the load carried by various units in the system to maintain tie line schedules and economic system operation.

This indicates an important part which speed governors perform to keep the system frequency within a desirable range, to maintain system stability and provide control to system operators enabling them to adjust generation for most economical loading of units in the power system.

2.3 Application and Performance

To determine the proper governor performance of hydraulic turbine applications typically the following information is required:

a) Type and size of turbine
b) Head, speed, discharge and runaway speed
c) WR^2 value for turbine and generator
d) Servomotor travel
e) Diameter and length of penstock or intake
f) Dimensions of scroll case and draft tube
g) Maximum allowable pressure rise
h) Maximum allowable speed rise
i) Gate and Runner blade timing
j) Plant operation, i.e. Peaking, Regulating or Base Load
k) Speed range required
l) Isochronous or Speed droop operation
m) Characteristics of prime mover
n) Characteristics of load

Once a governor is designed based upon the above mentioned information it controls the turbine output by adjusting the position of the wicket gates which control the water flow. The balance between power input and output from the generator is maintained by the governor. It operates continuously to correct the unbalance between output and input to the unit by opening and closing the wicket gates. The speed of the unit is kept constant within the values dictated by the permanent speed droop setting.

When a number of generating units are connected in parallel, it is necessary that all units simultaneously attempt to balance generation with load. In practice some units will have a limited participation in response to changes in system frequency and other units will be controlling the frequency. The desired response of various units is a function of governor settings and loading of transmission lines to which the units are connected. The frequency regulation is not only based upon the need of the customer for constant frequency but also to maintain power flows on transmission lines within limits and particularly of tie lines between interconnected systems. The accumulative speed error must be minimized due to the widespread use of electric clocks. Properly designed and adjusted governors should satisfy all the requirements outlined in Section 2.1.

2.4 Types of Governors

Earlier governors[1,3] were made of only mechanical components combined with hydraulic parts namely actuator and servomotor. First development was to replace the governor ball head sensing by permanent magnet generator (PMG) whose output variations were fed into a magnetic amplifier driving a force motor which actuates a pilot valve. Subsequent developments were aimed at the derivation of speed signal error from speed signal generator (SSG) and the use of operational amplifiers rather than magnetic amplifiers. These developments resulted in a faster response of governors to speed variations. At present, research, development and design of digital governors is well advanced but their application in industry has not been proven. The main parts of various types of governors are briefly described in the following Section. The most commonly used equation for a three term governor specification is given in Appendix B.

2.4.1 Mechanical Hydraulic Governor

The main parts of the mechanical governor consist of:

a) governor ball head
b) pilot and relay valves
c) servomotors
d) restoring mechanism
e) oil pressure system

Governor ball head responds to speed changes of the unit. Any change in speed causes a corresponding movement of the pilot valve. Pilot and relay valve are the intermediate portion of the governor which relay the motion of the ball head to the servomotors.

The restoring mechanism transmits the motion of the servomotor piston back to the actuator and in effect notifies it of the gate change. The servomotors are controlled by oil flow and oil flow is controlled by the relay valve.

Speed control is also obtained by rotating weights driven by a synchronous motor fed from the generator through a transformer or permanent magnet generator, coupled directly to the shaft of main generator. An increase in speed above normal causes the rotating weights to spread apart and forces the speeder rod downward so as to move the servomotor rod to close the gates. The main parts of mechanical governor are shown in the following Figure 2.1.

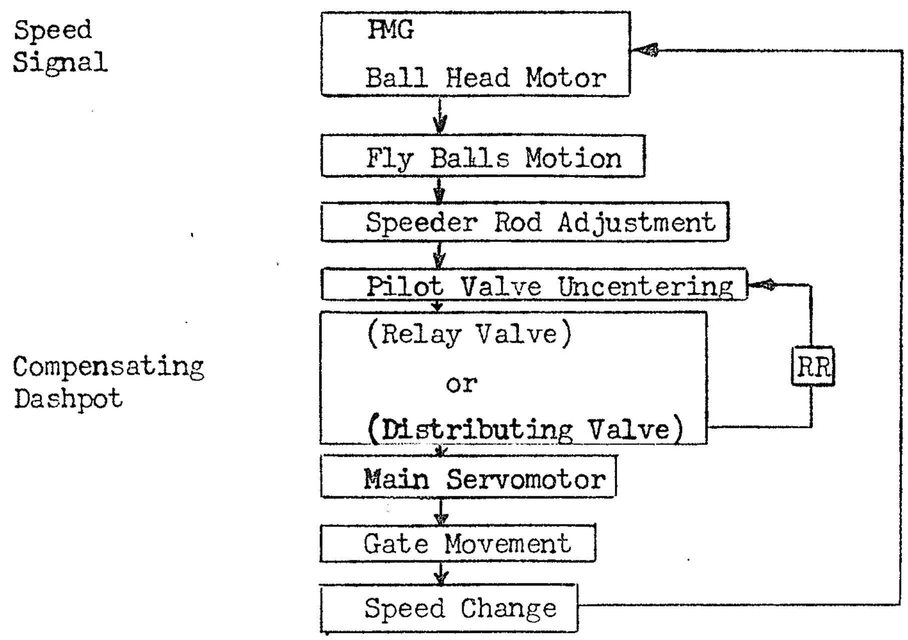


FIGURE 2.1

MAIN COMPONENTS OF MECHANICAL GOVERNOR

Because power system swings are slow, gates will tend to overtravel in the closing and opening direction and hunting will occur.

To prevent hunting due to overtravel of wicket gates, compensating dashpot is used to stop the gate movement before the unit speed returns to normal. Dashpot compensation is a stabilizing device to prevent hunting and its effect is of temporary nature. Block diagram of Mechanical-Hydraulic type governor is presented in Figure 2.2.

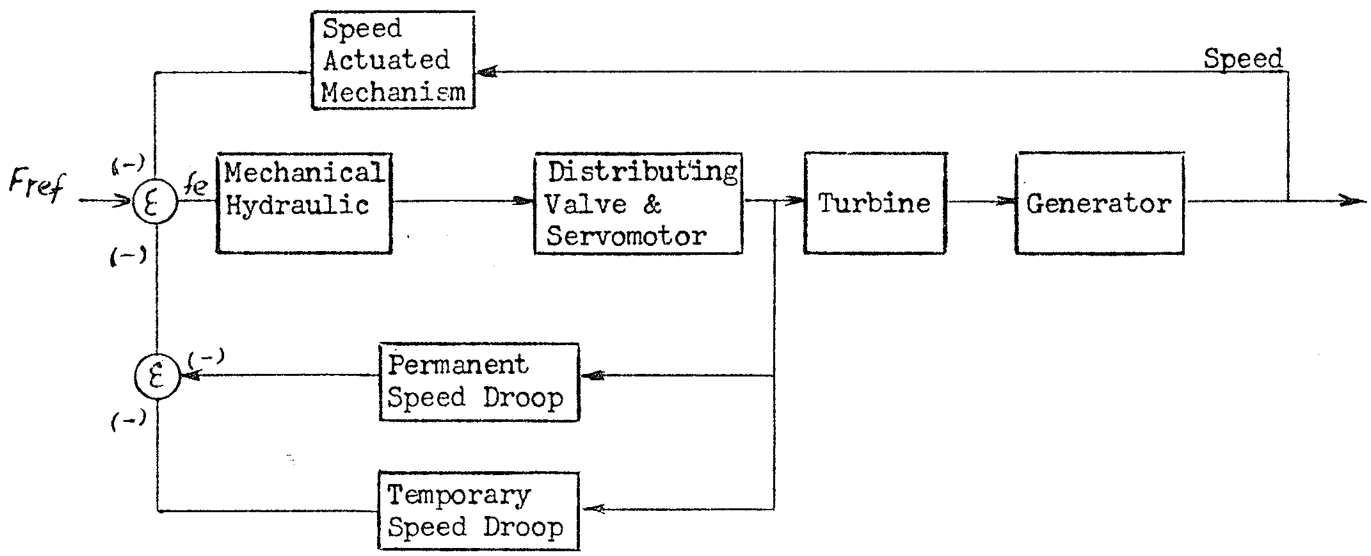


FIGURE 2.2

MECHANICAL-HYDRAULIC GOVERNOR BLOCK DIAGRAM

2.4.2 Electrical Hydraulic Governor

In this type of governor the pilot valve is activated by what is known as 'Force Motor'. Force motor consists of two coils of opposite polarity situated in magnetic field. As long as both windings create same amount of flux, no movement takes place. When flux becomes uneven, movement takes place. This movement when transferred to the pilot valve will cause the wicket gates position to change. Response of the force motor type governor is faster than the flyball type and has fewer mechanical parts.

Force motor, pilot servo-valve and transducer for feedback is called a transducer assembly. Magnetic amplifier used in this type of governor has other inputs such as speed droop, speed adjustment and speed error, etc. The main parts and block diagram of electrical hydraulic governor are shown in Figures 2.3 and 2.4 respectively.

Electrical

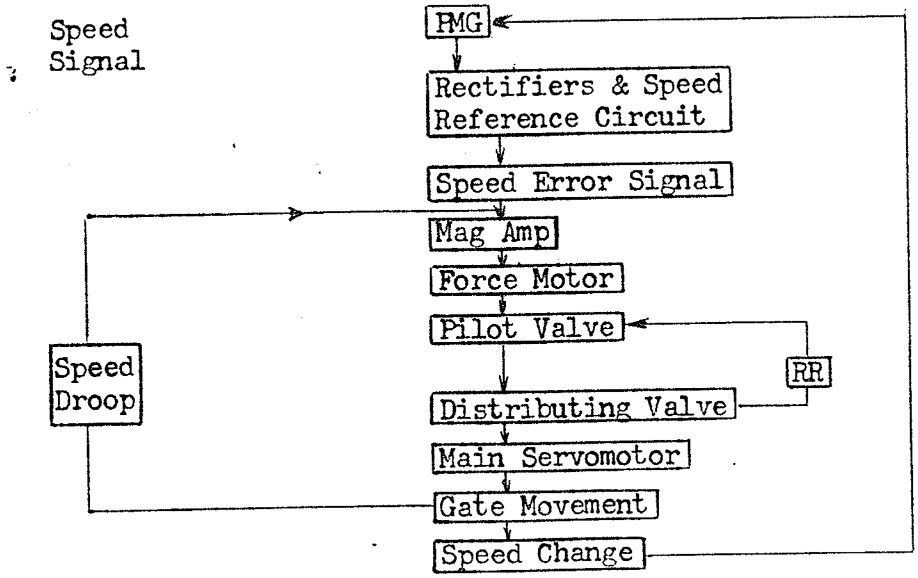


FIGURE 2.3

MAIN PARTS OF ELECTRICAL HYDRAULIC GOVERNOR

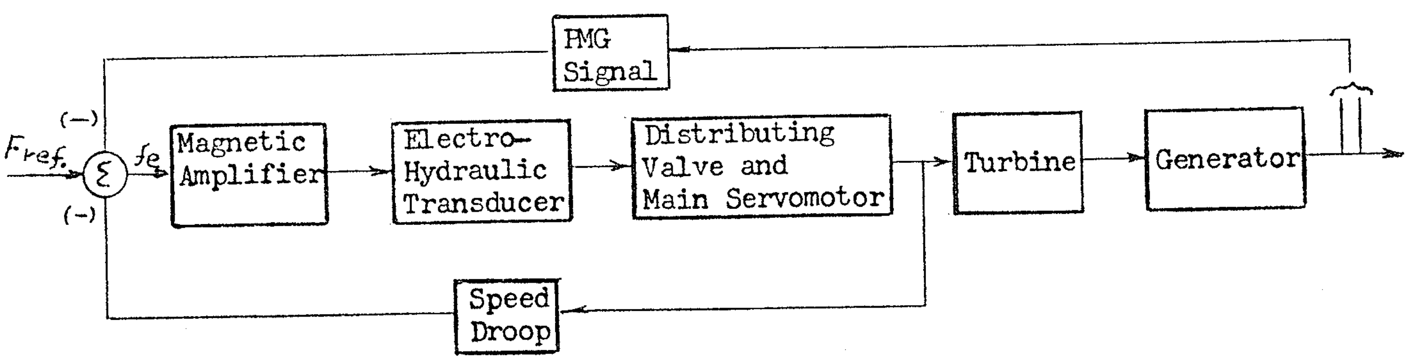


FIGURE 2.4

ELECTRIC HYDRAULIC GOVERNOR BLOCK DIAGRAM

2.4.3 Electronic Governor

The mechanical part is similar to the electrical and mechanical type governors but the speed sensing part is different. FMG is replaced by a device called Speed Signal Generator (SSG). SSG has a geared wheel with magnetic pick up mounted in close proximity to the teeth of the wheel. As the teeth pass the pick-up they cause pulses which are fed to a transistor amplifier. These pulses represent the speed of the unit and are fed into the control cubicle of the governor. The control section processes the signal through proportional, integral and derivative cards and through power amplifier to force motor. Feedback signal proportional to pilot servomotor position is supplied to the power amplifier input. This signal cancels the output of the integrator thus bringing the output of the power amplifier to zero and stops the pilot servomotor and consequently wicket gate travel. The main parts and block diagram of electronic type governor are shown in Figures 2.5 and 2.6 respectively.

Electronic

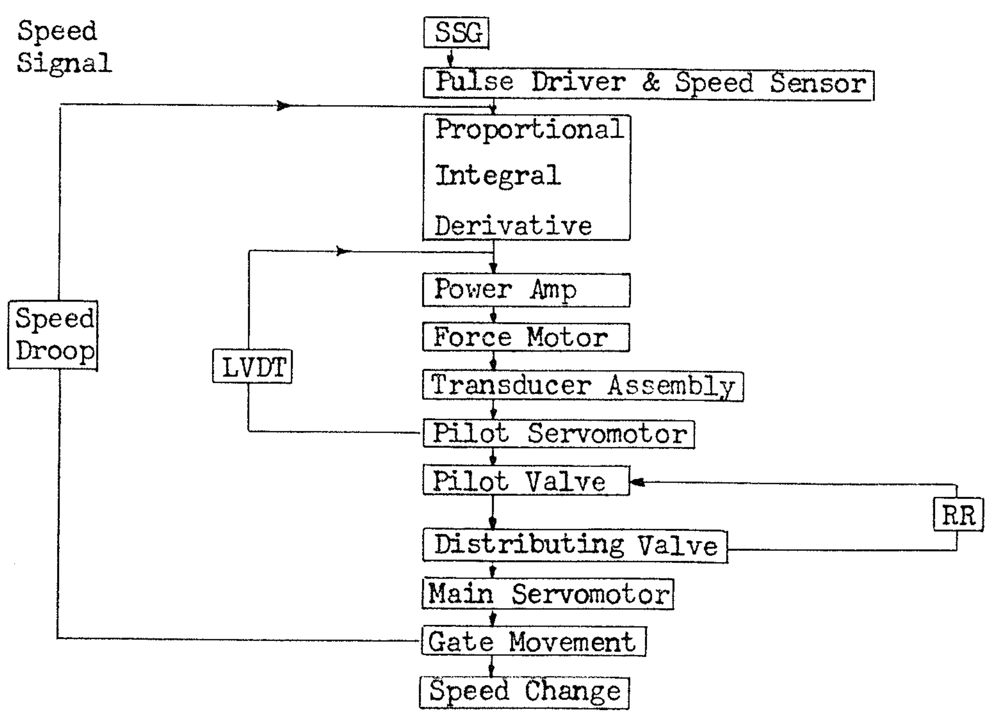


FIGURE 2.5

MAIN COMPONENTS OF ELECTRONIC GOVERNORS

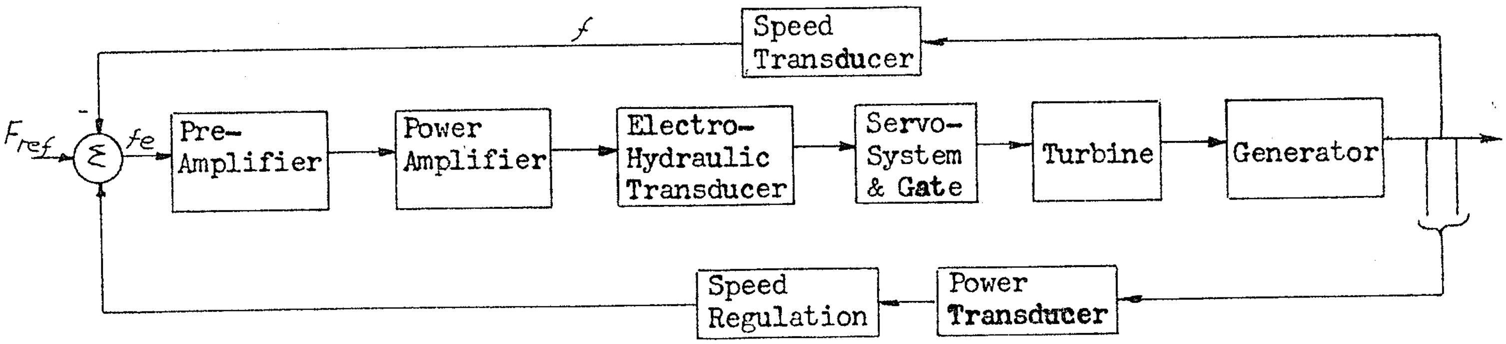


FIGURE 2.6

ELECTRONIC GOVERNOR BLOCK DIAGRAM

2.4.4 Digital Governor

The application of mini computer for speed control and generation control of a generating unit has been studied and published [8, 9] in the literature. In this scheme the heart of the system becomes a mini computer with associated input/output devices and software programs. The speed error control signal is processed in the mini computer and through a digital to analogue converter the control signal is applied to electro-hydraulic transducer. Most of the governor gain adjustments can be made by changing input data for the software program. The remaining part of the digital governor is identical to other types already described. Compared to other types, the digital governor has advantages which include the ability to incorporate adjustments to governor parameters with the minimum of hardware modifications and provides increased operator information display. Digital governor block diagram is given in Figure 2.7.

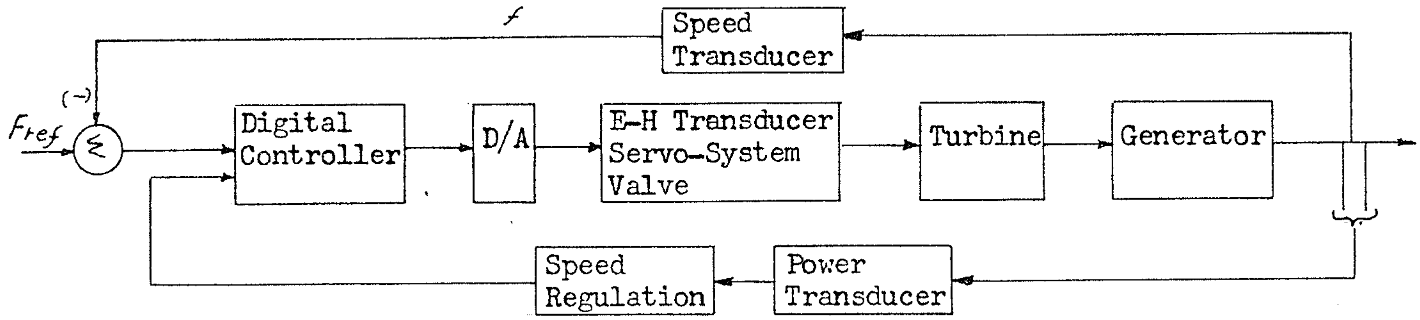


FIGURE 2.7

BLOCK DIAGRAM OF DIGITAL GOVERNOR

3. SPEED CONTROL CHARACTERISTICS OF BULB TURBINES

3.1 General

The bulb type unit is a horizontal shaft turbine generator housed in the water flow stream and in its present form is the result of more than 50 years of continuous development towards a design for a low head machine with minimum overall dimensions and cost. One of the major contributions to this development has been by Alsthom-Neyrpic[7] of France, with design work going on since 1923 and production since 1953. Probably the best known installation is that of Rance Estuary in Northwestern France. This is a tidal power scheme, built because of an earlier energy crisis in late 1950s. This development contains 24 Alsthom-Neyrpic 10 MW units. Alsthom-Neyrpic unit sizes have now increased to 54 MW, eight of which are to be installed at the Rock Island Plant on the Columbia River in Washington, USA.

Soviet Union has also been very active in the development and manufacturing of bulb type units since early sixties. In 1963 they produced their first unit of 20 MW capacity. These were followed in 1967 by 45 MW units for the Saratov Station on the Volga River[7] and since 1969 a series of 22 MW units have been produced in USSR.

In further attempts to reduce the size and costs, the straight flow turbine with generator mounted on the rim of the runner blade tips was developed. The scheme has proved to be practical only for small units. Presently in service and planned used of bulb units are shown in Table[7] Number 1.

TABLE 1

BULB UNITS OVER 1.0 MW

Country	Commissioned Or On Order	Planned	Total
Austria	24		24
Belgium	4		4
Canada	6	25	31
France	91	4	95
Germany	55		55
Hungary	4		4
India	7		7
Italy	1		1
Japan	16		16
Korea	6		6
Norway	1	1	2
Roumania		9	9
Spain	2	9	11
Sudan	3		3
Sweden	10		10
Switzerland	9		9
USA	8	3	11
USSR	58		58
Yugoslavia	9		9
		TOTAL	365

3.2 Operating Features of Bulb Type Units

In order to realize the benefits of bulb turbine the diameter of the generator stator is minimized. This results in much smaller rotor inertia H than for a comparable vertical unit and results in a small acceleration time constant T_a.

The water passage of bulb turbines is hydro dynamically superior to vertical units. The latter having spiral cases and right angle change of direction into the draft tube. In bulb units higher velocities can be tolerated and lead to high values of water starting time T_w. This departure of water starting time T_w from vertical units results in:

a) Degradation of Governor Control

There is degradation of speed control when operating the unit isolated from the system but when unit is synchronized to the system, speed control is no problem as long as effective excitation control is maintained. Without automatic voltage regulation, pole slipping is possible.

b) High Overspeed on Load Rejection

Unit will reach higher overspeed on load rejection and this is due to large water starting time T_w. The gate timing cannot be reduced very much because this will result in water hammer and separation of water column, and high increase in water pressure on the intake side. That is why these units are designed for higher overspeed on load rejection.

Bulb units at Jenpeg are designed for sustained runaway speed and no intake headgates are provided. Two sets of steel stoplogs for two intakes are provided, one for normal unwatering and one for emergency use in the event of the wicket gates failing to close.

The bulb units, where applicable, have a number of advantages over conventional vertical Kaplan units and result in an overall economical powerhouse design, such as:

a) High specific output (small diameter runner)
b) Improved cavitation characteristics
c) Improved draft tube efficiency
d) Simplified powerhouse design

Some of the typical data for Jenpeg units is given below:

Mechanical Starting Time constant T_m	1.8 seconds
Water Starting Time constant T_w	4.9 seconds
Gate Timing	10 seconds
Blade Opening Time	20 seconds
Blade Closing Time	40 seconds
Maximum overspeed on full load rejection under rated conditions with normal governor operation	180%

It is estimated that the water surrounding the runner tends to increase the effective mechanical starting time constant T_m. For Jenpeg units this increase is considered to be in the order of 0.8 seconds, thus increasing the total mechanical starting time T_m to 2.6 seconds.

3.3 Bulb Type Units at Jenpeg

The Jenpeg Generating Station is located some 320 miles north of Winnipeg and is a part of the Lake Winnipeg Regulation Project, the main purpose of which is to regulate water levels and outflows of Lake Winnipeg which forms a large reservoir for the Nelson River. The head at Jenpeg varies from 16 feet to 40.6 feet. The operating range for bulb turbines has been selected from 16 to 35 feet and the rated head is 24 feet. For net heads in excess of 35 feet the units will be shut down.

Because of the variation in head and the duration of time the units will operate at heads other than rated, it was considered necessary to use Kaplan units. While the cost of the bulb units is somewhat higher than for the vertical type units, the overall cost of the powerhouse is some 15% lower for the bulb type units. The bulb unit selected for Jenpeg has a nominal rating 28 MW, 0.9 power factor leading and is supplied by USSR[7,10,12].

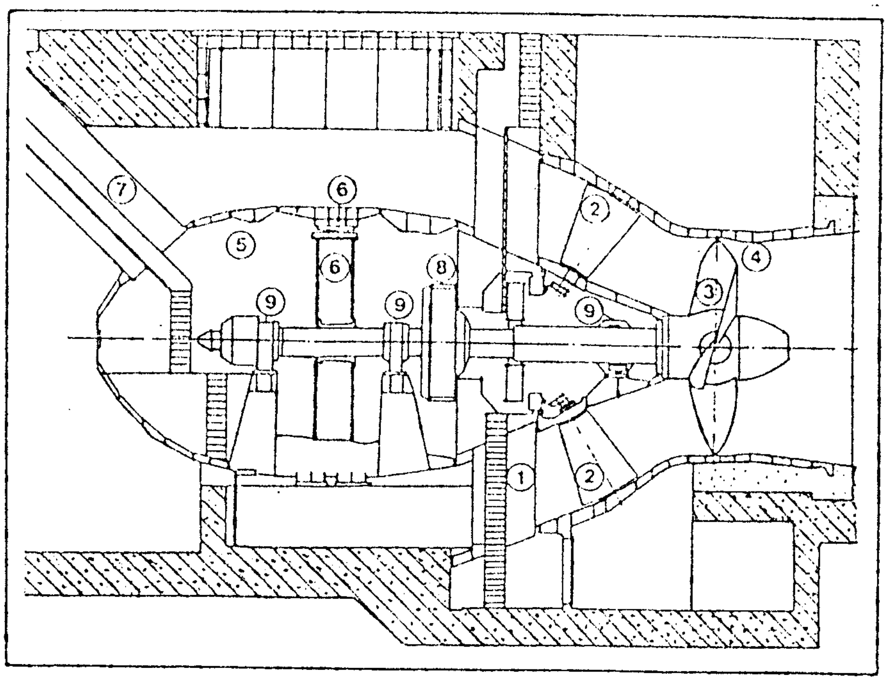
Each unit consists of a horizontal Kaplan turbine driving the generator and forms the major part of the bulb. The governor, excitation system, generator bus duct, lubrication system, generator cooling water and bus duct installation are the other sub-systems associated with the bulb unit. Some of the pertinent data for Jenpeg Station's bulb units is as follows:

General	Data
No. of turbine generator units	6
Type of units	Kaplan (variable pitch propeller)
Spacing in powerhouse	62 ft.
Diameter of bulb	31 ft.
Length	77 ft (overall)

Turbine and Generator	Data
Rated Head	24 ft.
Maximum Operating Head	35 ft.
Minimum Operating Head	16 ft.
Turbine Ouput at Rated Head	28,900 kW
Maximum Output	32,000 kW
Rated Discharge	15,900 cfs
Runner Diameter	24.64 ft.
No. of Blades	4
No. of Wicket Gates	16

Turbine and Generator	Data
Rating	28 MW, 31.1 MV.A 0.9 power factor
Voltage	4.16 kV
Synchronous Reactance	0.84 pu
Transient Reactance	0.32 pu
Sub-Transient Reactance	0.24 pu
Cooling	Demineralized Water (Rotor & Stator)
Rated Speed	62.1 rpm
Runaway Speed - On Cam.	140 rpm
Runaway Speed - Off Cam.	192 rpm

The general arrangement of generator and turbine[10] to form the bulb unit is shown in Figure 3.1.



Cross section of Jenpeg bulb turbine generator. Key to numbers: 1: stator, 2: wicket gate assembly; 3: runner with moveable blades, 4: runner chamber and draft tube, 5: bulb on concrete pier, 6: generator rotor and stator, 7: maintenance access tube, 8: thrust bearings, 9: bearings of bulb unit.

FIGURE 3.1

GENERAL ARRANGEMENT OF BULB TURBINE AND GENERATOR

3.4 Governor System for Jenpeg Units

The governors are the electric hydraulic type with adjustable temporary droop and derivative gain characteristics. The governor system for Jenpeg units is required to control the speed of low inertia units. Hydraulic torque fluctuations of bulb turbines give rise to fast speed fluctuations which governing system must control for stable operation of the unit. The controlling functions are achieved by electrical circuits which in turn control the output of a suitable transducer and through few stages of hydraulic amplification operate the main servomotors. A brief review of the governor equipment for Jenpeg units is given below:

Speed Sensing

The speed signal is derived from the AC generator mounted on the main generator shaft and is connected to the dead band device.

Derivative Term

The signal from the dead band device is applied to the input of operational amplifier through RC derivative circuit. The derivative time constant T_n is adjustable in this module.

Permanent and Temporary Droop

The signal from derivative term module is applied to error signal amplifier along with speed adjust signal. Permanent and temporary droop signals are also provided as input to the error signal amplifier and are derived as shown in the Figure 3.2. Provision is also made to transfer settings from no-load to on-load operation dependent upon an auxiliary contact of the generator breaker.

Permanent and temporary droop settings provide negative feedback across the high gain error signal amplifier and determine the forward proportional gain of the governor system.

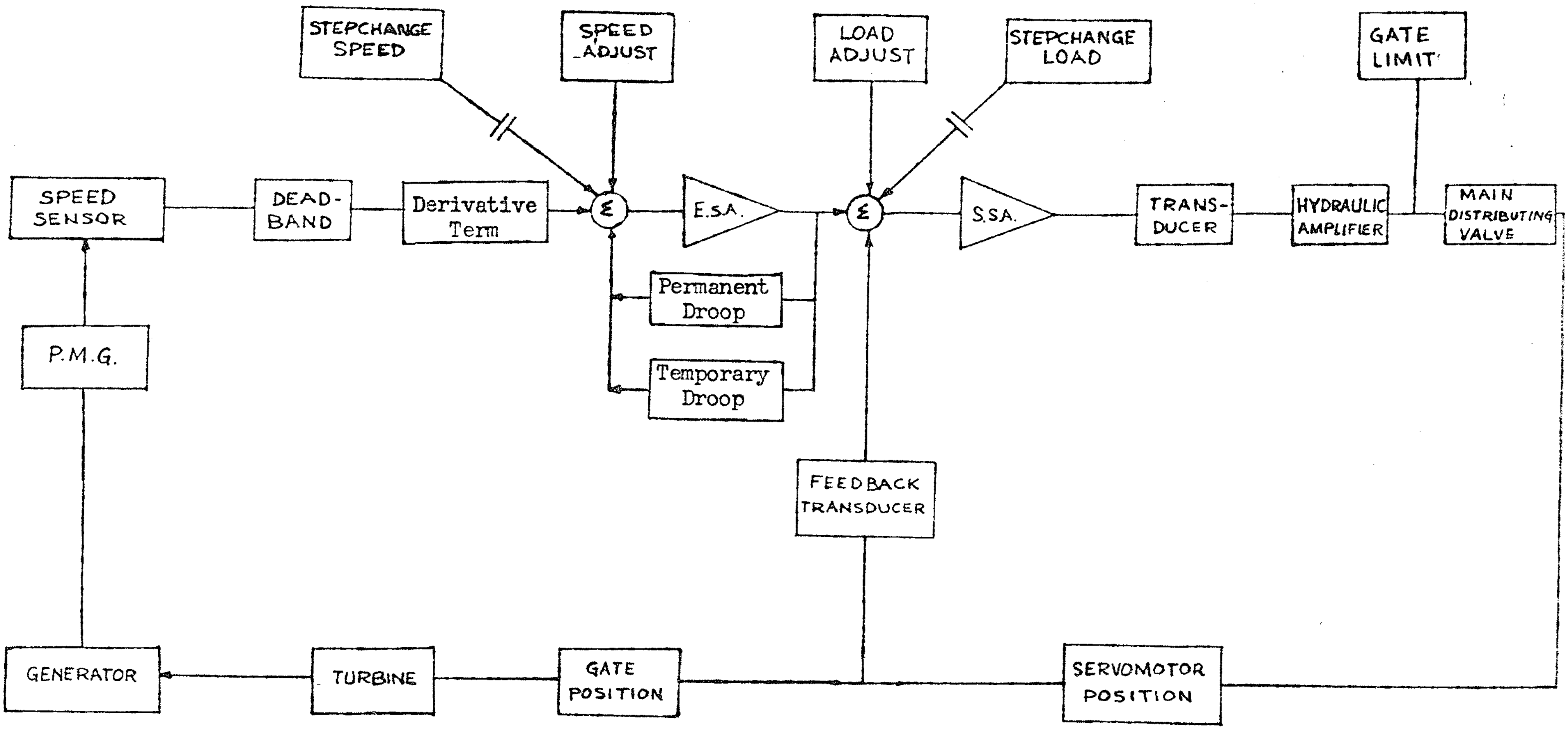


FIGURE 3.2

SIGNAL FLOW DIAGRAM OF JENPEG GOVERNOR SYSTEM

* E.S.A. Error Signal Amplifier

S.S.A. Signal Summing Amplifier

Power Amplifier

The output of error signal amplifier is further amplified to raise the power level of the signal sufficiently to operate the coils of the electro-hydraulic transducer. Power amplifier (SSA) also accepts as input signals from load adjust device and gate feedback transducer. Amplified output is applied to the transducer coil where it is converted into mechanical output.

Transducer and Hydraulic Amplifier

Transducer consists of ring shaped permanent magnet and spring suspended coil arranged in the gap. When power amplifier output signal is applied to the coil, it moves upward or downward depending upon the direction of current flow, the distance being proportional to the level of the signal. When coil is de-energized it is held in the middle position by springs. The coil movement leads to piston plunger's upward or downward displacement.

Provision is made for governor operation under manual or automatic control. On manual control, the output from electrical circuits of the governor is disconnected and the transducer output signal has no effect on the movement of the piston plunger.

Blade and Gate Distributing Valves

Separate distributing valves are provided for blade and gate displacements. Provision is made for control of gate valve plunger through gate limit shaft lever on manual and automatic control. Blade valve plunger is controlled by blade control mechanism manually or by three dimensional (3D) cam automatically. Movement of the gate distributing valve plunger disturbs the force balance on servomotor piston by directing the pressure oil to one side of the gate servomotor. Upon gate movement the restoring shaft rotates and turns 3D cam, thus displacing blade distributing valve plunger to control the oil flow to the opening or closing side of the blade servomotor. The blade servomotor positions the blades at a new angle in compliance with gate-blade relationship for the given head. Figures 3.3(a) and 3.3(b) represent the detailed and simplified block diagram of Jenpeg governor system.

Permanent Magnet Generator

As the gate and blade displacement take place, the unit speed changes and is fed back to the speed sensor by PMG output. PMG is driven by the unit shaft and provides AC voltage to the governor speed sensor, tachometer and the overspeed protection relay.

The governor power supply units are also fed by PMG output. At and above 80% rated speed the PMG output is applied to the governor circuits and power supply units.

In addition to the above the following additional control mechanisms of governor system for bulb type units are necessary and a brief description of their functions is also provided.

3.4.1 Start-Stop Mechanism

To start the unit, starting solenoid is energized which removes the spring held latch thereby releasing the plunger upward under a spring force thus permitting the wicket gates to open. When starting procedure is completed, the starting solenoid is de-energized. To stop the unit, shutdown solenoid is energized which displaces the plunger downward where it is latched by a spring loaded latch. Oil pressure is supplied to the upper side of the piston resulting in a downward movement to fully close the wicket

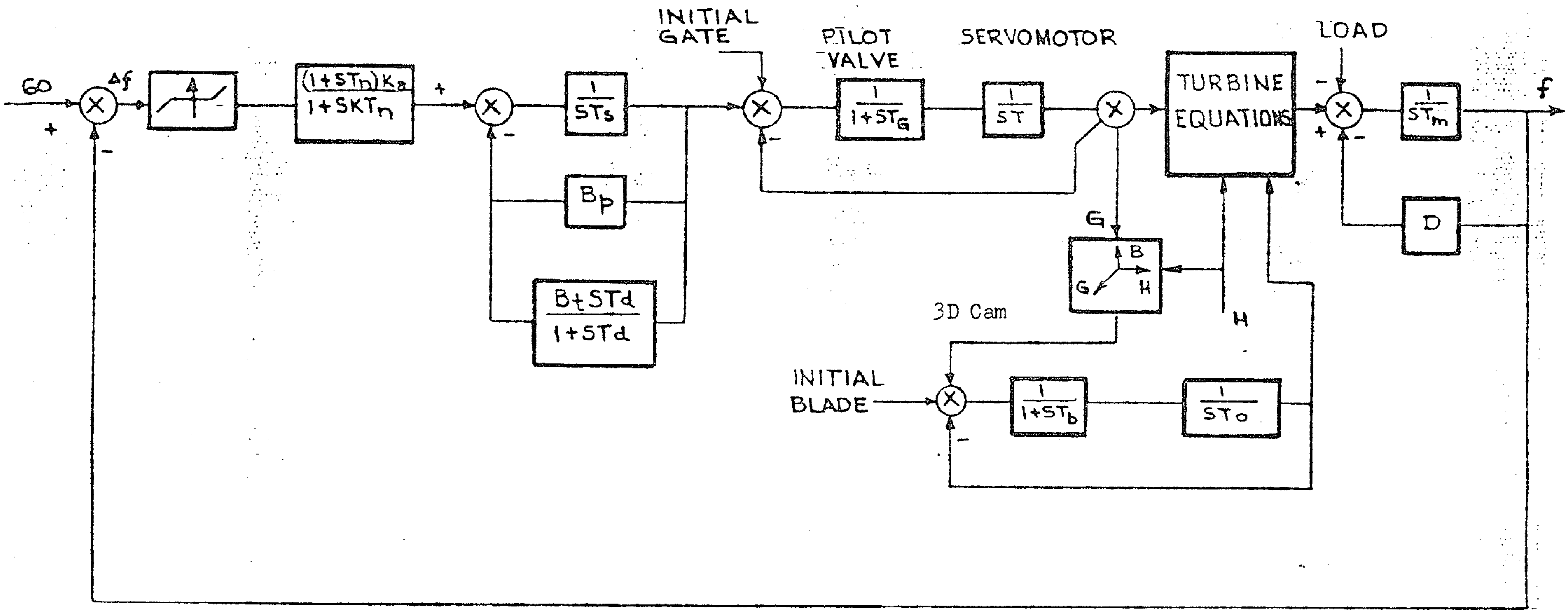


FIGURE 3.3 (a)

DETAILED BLOCK DIAGRAM OF JENPEG GOVERNOR SYSTEM

NOTE:

T_G = 0.6 sec
T = 0.02 sec
T_o = 0.01 sec
T_b = 1.7 sec
DEAD BAND = ±0.02

T_n = 0 — 1.0 (Typical 0.1 sec)
T_s = 0.03 sec (fixed)
B_p = 0 – 10%
T_d = 0 – 30.0 sec

K = 0.1
K_a = 0.1
B = Blade Angle
G = Gate Position
H = Head
D = Damping

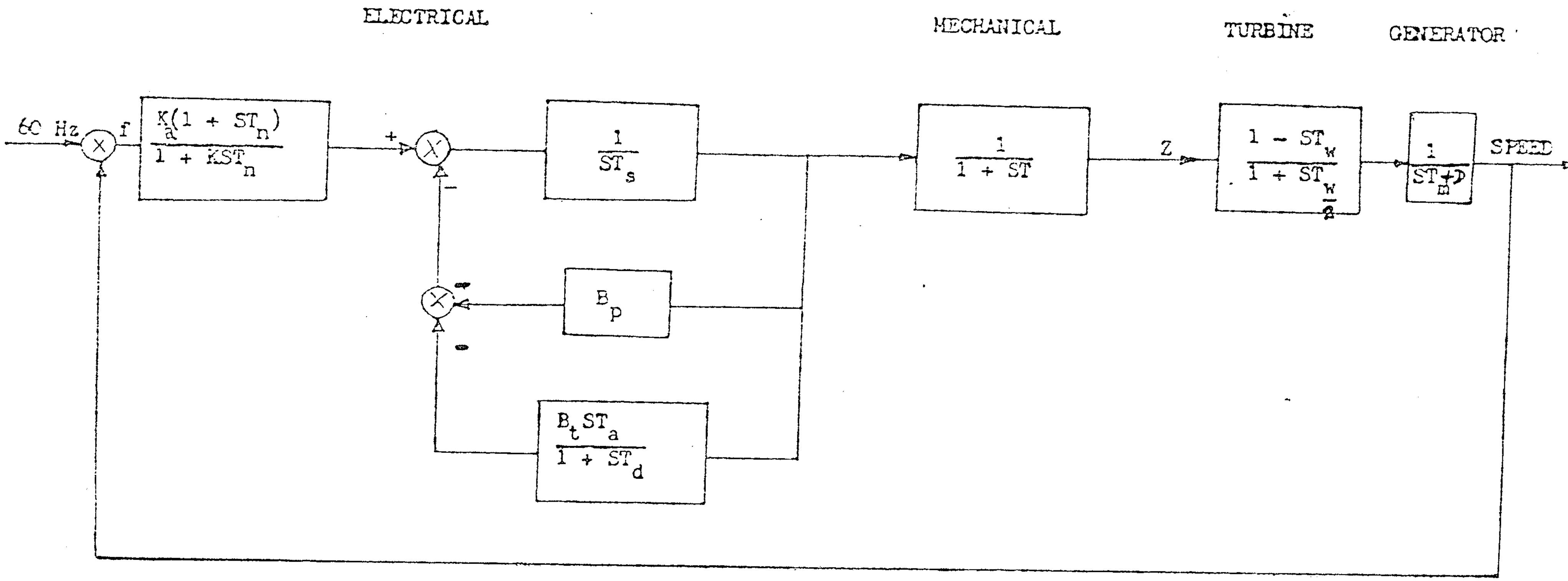


FIGURE 3.3 (b)

SIMPLIFIED BLOCK DIAGRAM OF JENPEG GOVERNOR SYSTEM gates. When the gates are fully closed and the unit has come to full stop, shutdown solenoid is de-energized. Normally the distributing valve plunger is slightly displaced for closing from the centred position thus directing oil pressure to produce an additional force to keep the gates closed.

3.4.2 Speed No-Load Mechanism

This mechanism is used to set the wicket gates at starting gate opening and limits the wicket gates from opening more than starting gate opening. This is achieved by a solenoid which is called speed no-load solenoid. The speed no-load solenoid is energized at unit start and limits the gate opening to starting gate opening. When the generator is synchronized to the system the speed no-load mechanism is de-energized thus allowing the wicket gates to open up to 100%.

This mechanism also provides contacts of limit switches for control and annunciation.

3.4.3 Gate and Blade Control Mechanism

For maximum turbine efficiency under various heads the correct relationship between the turbine gate positions and blade angles should be maintained. To achieve proper relationship between blade angles and gate positions, a three dimensional cam has been designed on basis of experimental curves to provide optimum turbine efficiency at any gate opening and head.

Due to load changes, gate movement takes place and through the restoring shaft mechanism and additional mechanical linkages the 3D cam is rotated to displace a plunger to control the oil flow to the opening or closing side of the blade angle servomotor which positions the blades at a new angle according to gate-blade relationship for a given head. Blade servomotor restoring connections recentre the displaced plungers thereby stopping the movement of blade servomotor.

3.4.4 Effect of Head on 3D Cam Position

Position of 3D cam is adjusted according to variations in head. This control of 3D cam position can be manual or automatic. In automatic mode of operation, upon change of head, a signal is generated in the governor which upon amplification moves the 3D cam through a motor and gear arrangement to a predetermined position for the new head. The movement of 3D cam rotates a feedback potentiometer and a feedback signal is applied to the amplifier in the governor cubicle.

This mechanism also modifies the value of starting gate opening in accordance with head deviation and protects the unit from overload by limiting the value of maximum gate opening when head increases. This is achieved by the wedge with two profiles and being moved by 3D cam. The upper profile limits the maximum opening and the lower profile limits the starting opening at a given head. Starting gate opening decreases on high head and increases on low head.

3.4.5 Programmed Closing Mechanism

The purpose of the programmed closing is:

i) To provide blade angle control at unit start and shutdown.
ii) To provide programmed closing of the wicket gates and tilting of the blades at load rejection.

Programmed closing is energised when blade tilt solenoid (BTS) is energized. As a result wicket gates are closed to a predetermined and pre-adjusted gate opening and blade angle is changed to the blade angle adjusted for unit starting.

When wicket gates are closed, energizing and de-energizing the blade tilt solenoid does not effect the wicket gates but the blade angle only. Two speed switches are provided to control BTS during unit start, stop and at load rejection.

A single line schematic of Jenpeg governor system which shows the relationship of the above mentioned mechanisms is given in Figure 3.4.

The effect of these mechanisms upon the speed characteristics of the units is presented in the following Chapter.

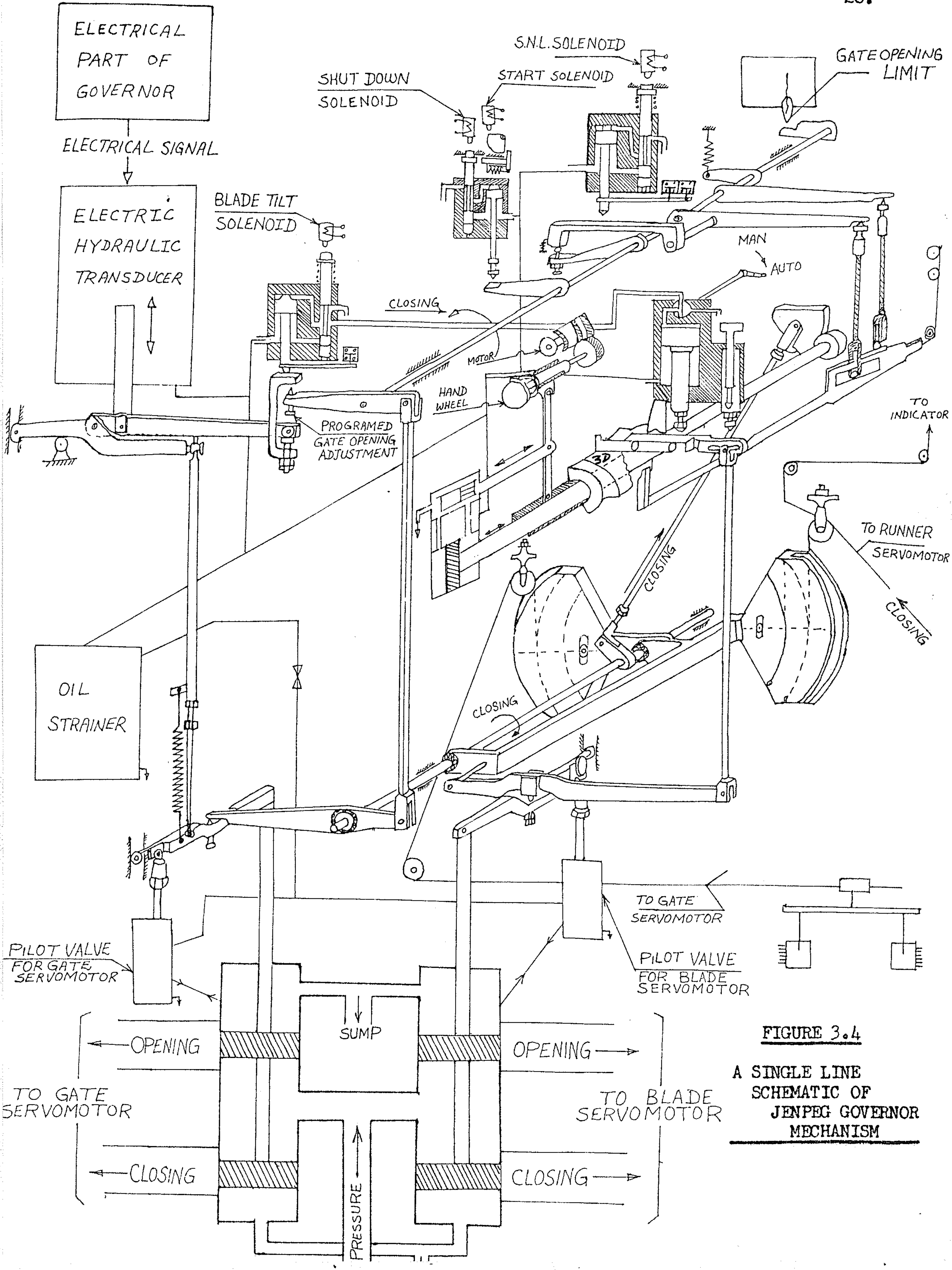


FIGURE 3.4

A SINGLE LINE SCHEMATIC OF JENPEG GOVERNOR MECHANISM

4. FIELD TESTS AND RESULTS

4.1 General

Previous chapters describe the governor equipment for hydraulic turbines and this chapter deals with field tests necessary to make governor adjustments for proper operation of the bulb type units under different load conditions. The test results obtained during field tests are also discussed. These tests include off line and on line operation and adjustments when the unit is dewatered. Governor response to small disturbances at speed no-load and when synchronized to the system are reported. The operation and effect of various adjustments on speed control of the unit during load rejection tests are also presented.

4.2 Unit Start on Governor Control

When unit start is initiated [7,11] the unit start solenoid and blade tilt solenoid (BTS) are energized. The gate opening limiter moves to 100% and the unit gates open to a starting gate opening position. The restoring connections recentre gate opening plunger through restoring cable, weight, eccentric levers, etc. Blades are set at the starting angle by blade tilt solenoid and the control of blade angle is 'OFF CAM' until the unit reaches 50% rated speed.

The unit accelerates and at 50% rated speed a speed switch de-energizes blade tilt solenoid. At the same time the control of blade angle is transferred to 'ON CAM' and blade angle changes to a predetermined gate and blade characteristics. Once the predetermined relationship of gate-blade control is reached, the restoring connections recentre the blade servomotor plunger.

Once the speed reaches 80% of rated speed, the governor circuits are placed in operation and at 100% rated speed the wicket gates are placed under governor control and wicket gates are positioned at speed no-load opening. Then the unit can be manually or automatically synchronized to the system and upon generator breaker closing, speed no-load solenoid is de-energized and gate opening limit dependent upon speed no-load mechanism is removed permitting the gates to open up to 100%.

Figures 4.1 (a) to 4.1 (e) show the gate opening and blade angle position during unit start for various values of B_p, B_t, T_d and T_n.

Where: B_p = Permanent speed droop

B_t = Temporary speed droop

T_d = Damping time constant

T_n = Acceleration time constant

4.3 Governor Response to Small Step Disturbance at Speed No-Load

Once unit start has been successfully completed the next test is to check the governor response and make adjustments to temporary and permanent droop, acceleration time and damping time constant. The gate and speed traces were recorded for various values of B_p, B_t, T_d and T_n and are shown in Figures 4.2 (a) to 4.2 (d). It can be seen from Figure 4.2 that the adjustment of T_n value can either make governor response damped or oscillatory.

The effect of different values of B_t, T_d, B_p and T_n on speed and gate curves is also presented in Appendix C. The calibration curves for these gain adjustments along with a basic governor block diagram are also included.

The simulation of load rejection at speed no-load is carried out to determine the response of the unit following load rejection when synchronized to the system. Figure 4.2 (d) is such a simulation carried out at speed no-load. The gate, speed and blade angle were recorded

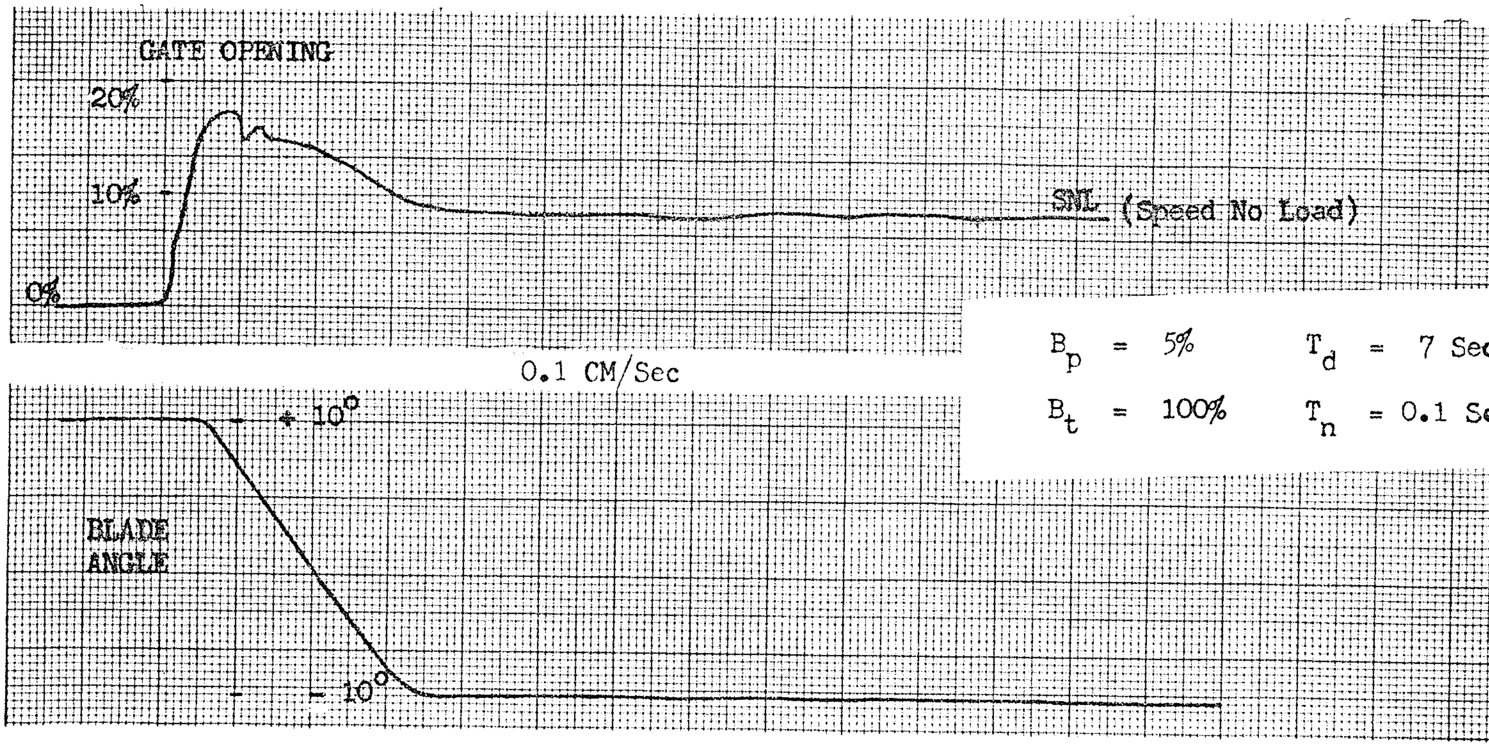


FIGURE 4.1 (a)

GATE OPENING AND BLADE ANGLE DURING UNIT START

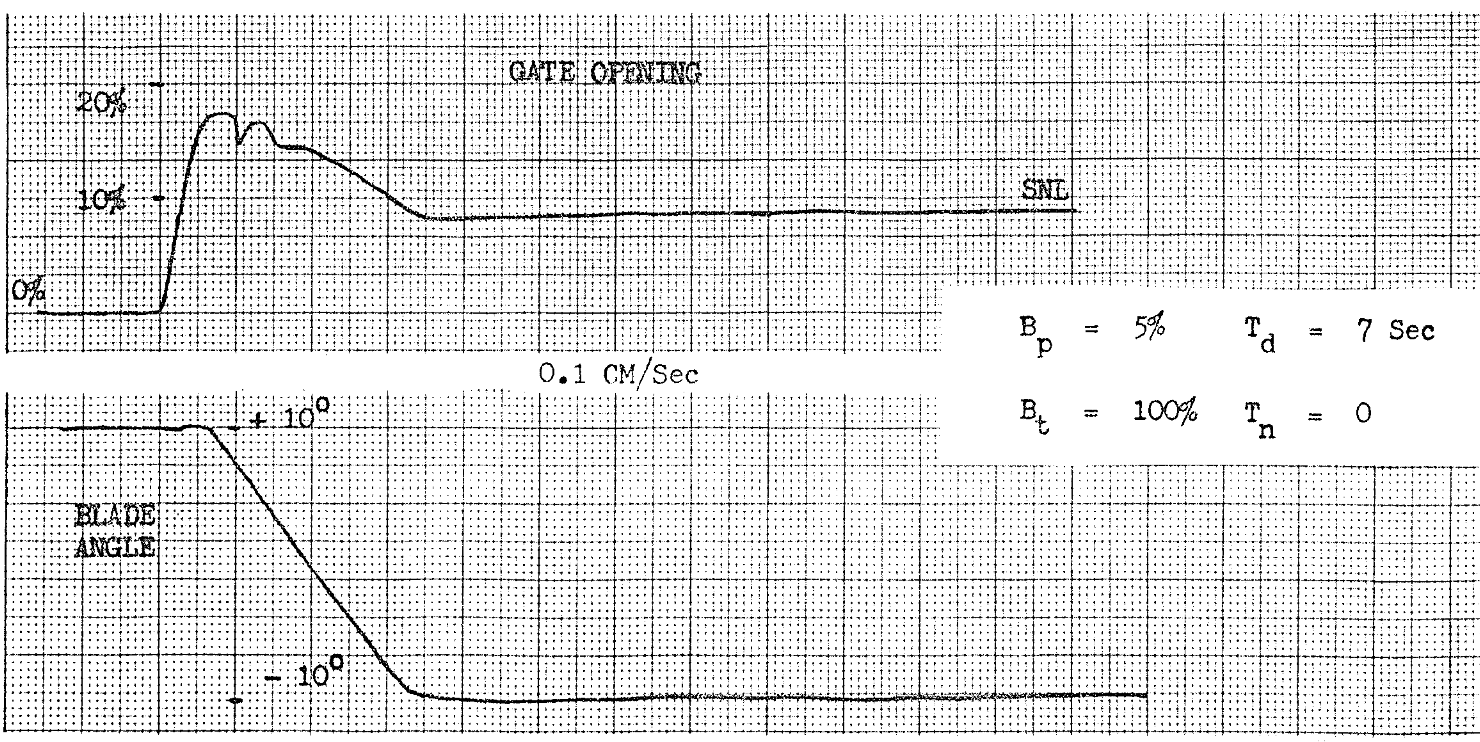


FIGURE 4.1 (b)

GATE OPENING AND BLADE ANGLE DURING UNIT START

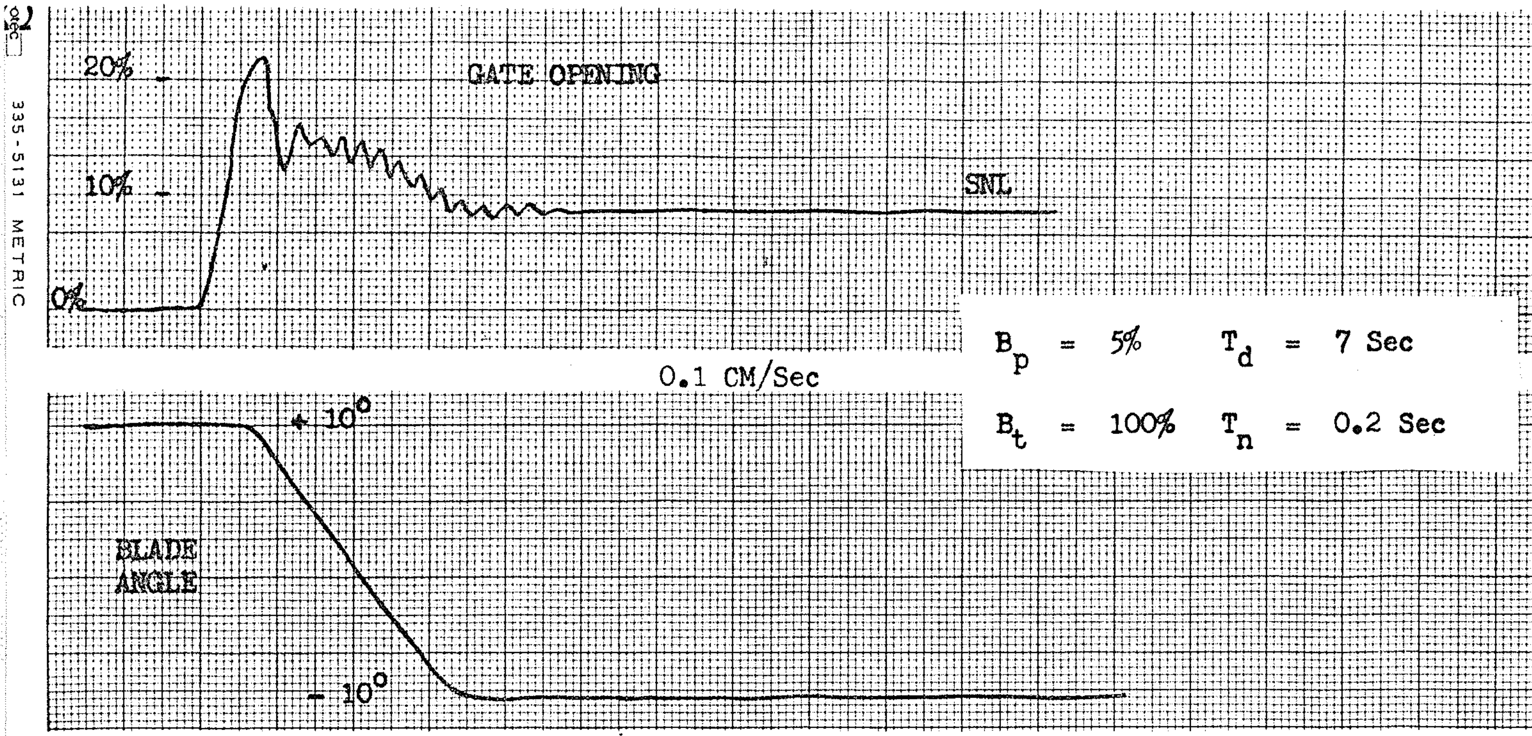


FIGURE 4.1 (c)

GATE OPENING AND BLADE ANGLE DURING UNIT START

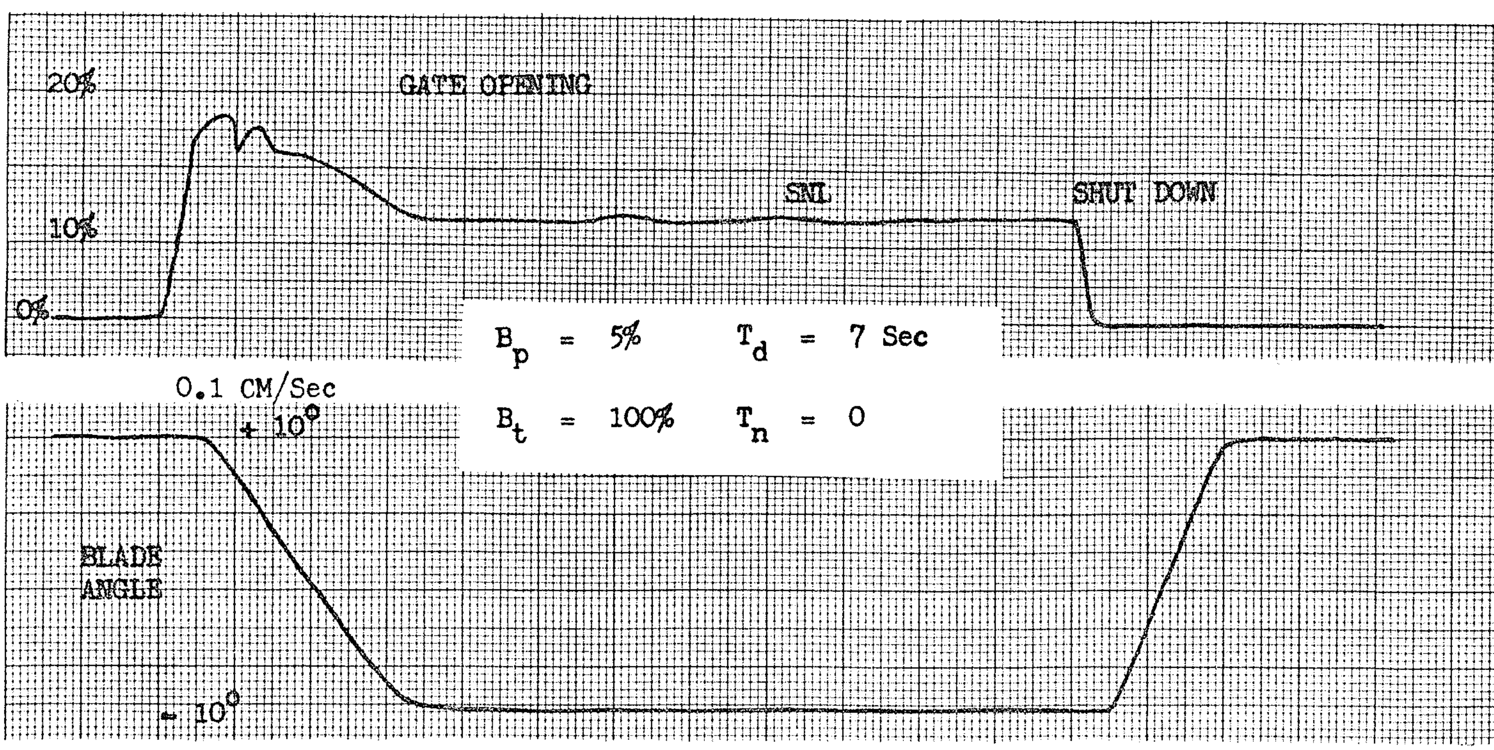
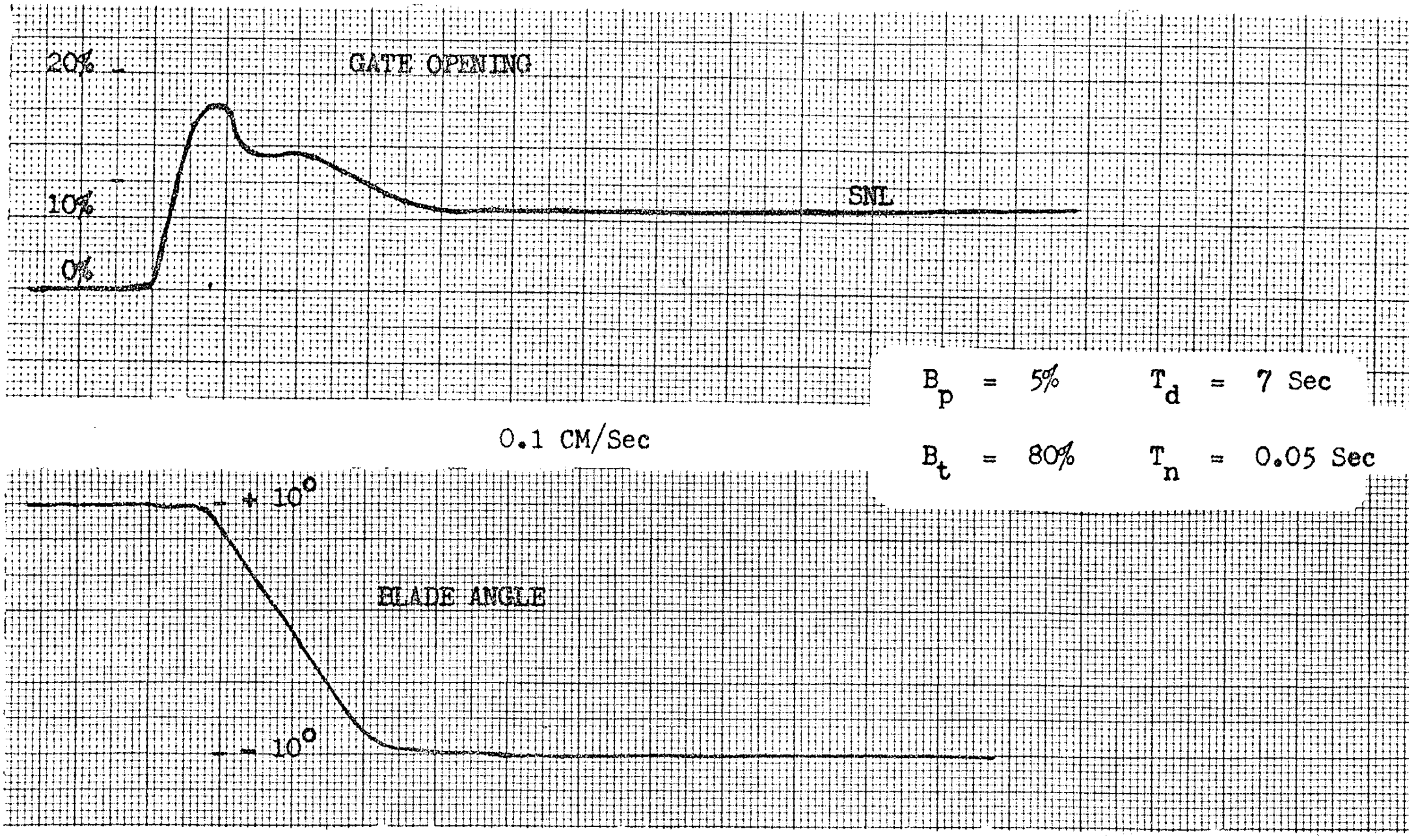


FIGURE 4.1 (d)

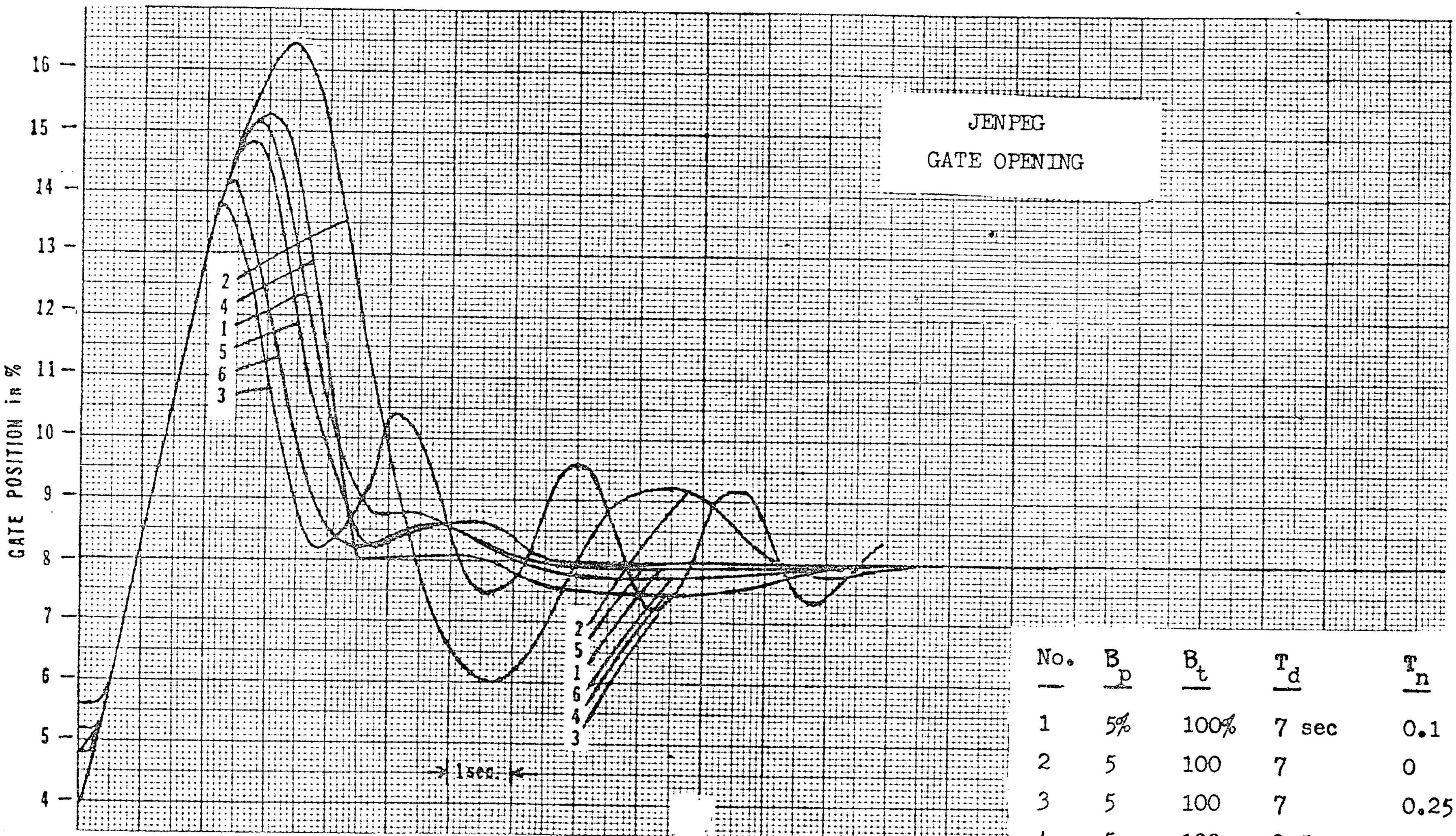
GATE OPENING AND BLADE ANGLE DURING UNIT START



B_p	=	5%	T_d	=	7 Sec
B_t	=	80%	T_n	=	0.05 Sec

FIGURE 4.1 (e)

GATE OPENING AND BLADE ANGLE DURING UNIT START



No.	B_p	B_t	T_d	T_n
1	5%	100%	7 sec	0.1 sec
2	5	100	7	0
3	5	100	7	0.25
4	5	100	3.5	0.1
5	5	80	7	0.1
6	5	80	16	0.1

FIGURE 4.2 (a)

GATE OPENING OBTAINED DURING GOVERNOR RESPONSE TESTS

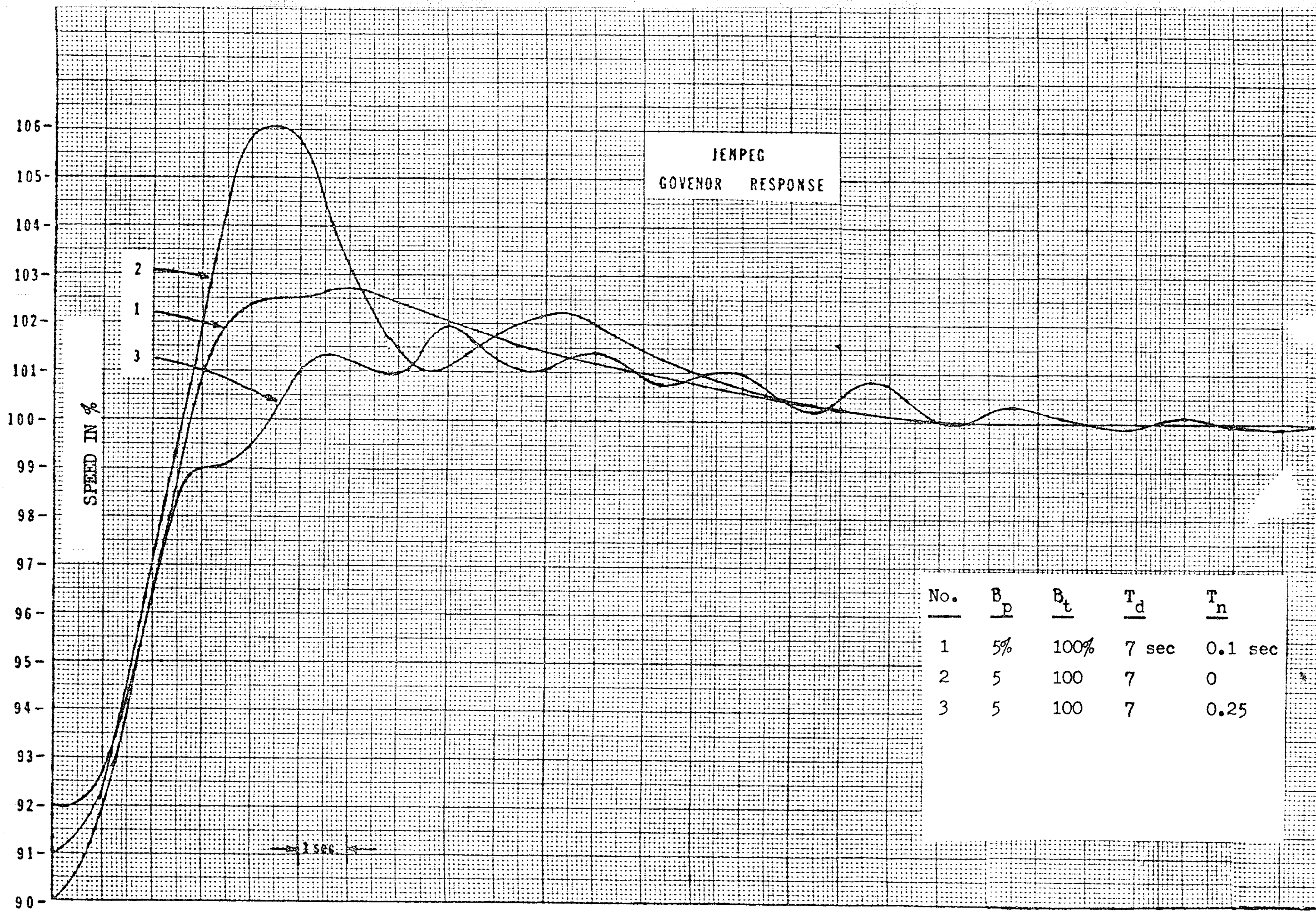
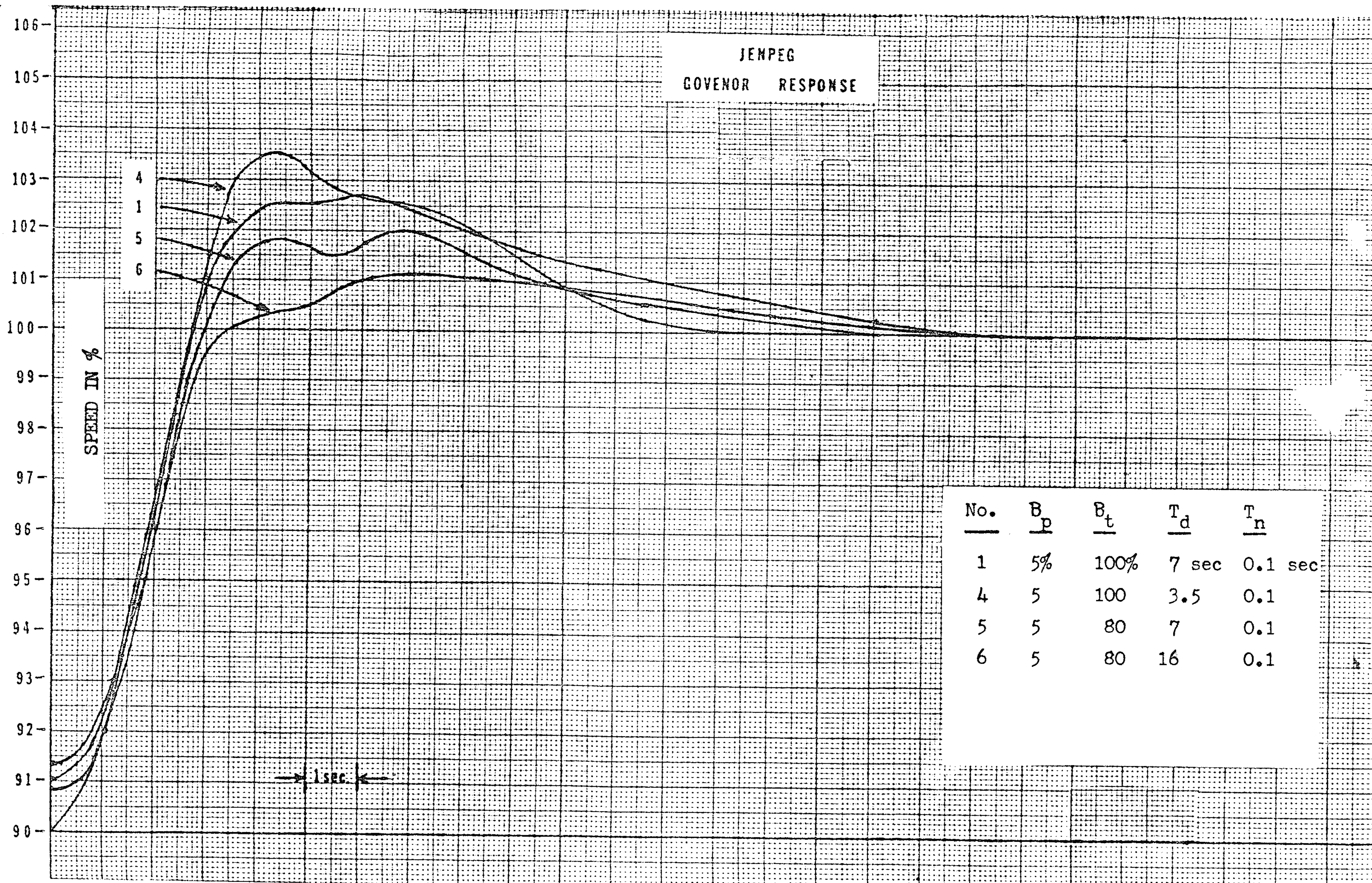


FIGURE 4.2 (b)

UNIT SPEED RECORDED DURING GOVERNOR RESPONSE TESTS



No.	B_p	B_t	T_d	T_n
1	5%	100%	7 sec	0.1 sec
4	5	100	3.5	0.1
5	5	80	7	0.1
6	5	80	16	0.1

FIGURE 4.2 (c)

UNIT SPEED RECORDED DURING GOVERNOR RESPONSE TESTS

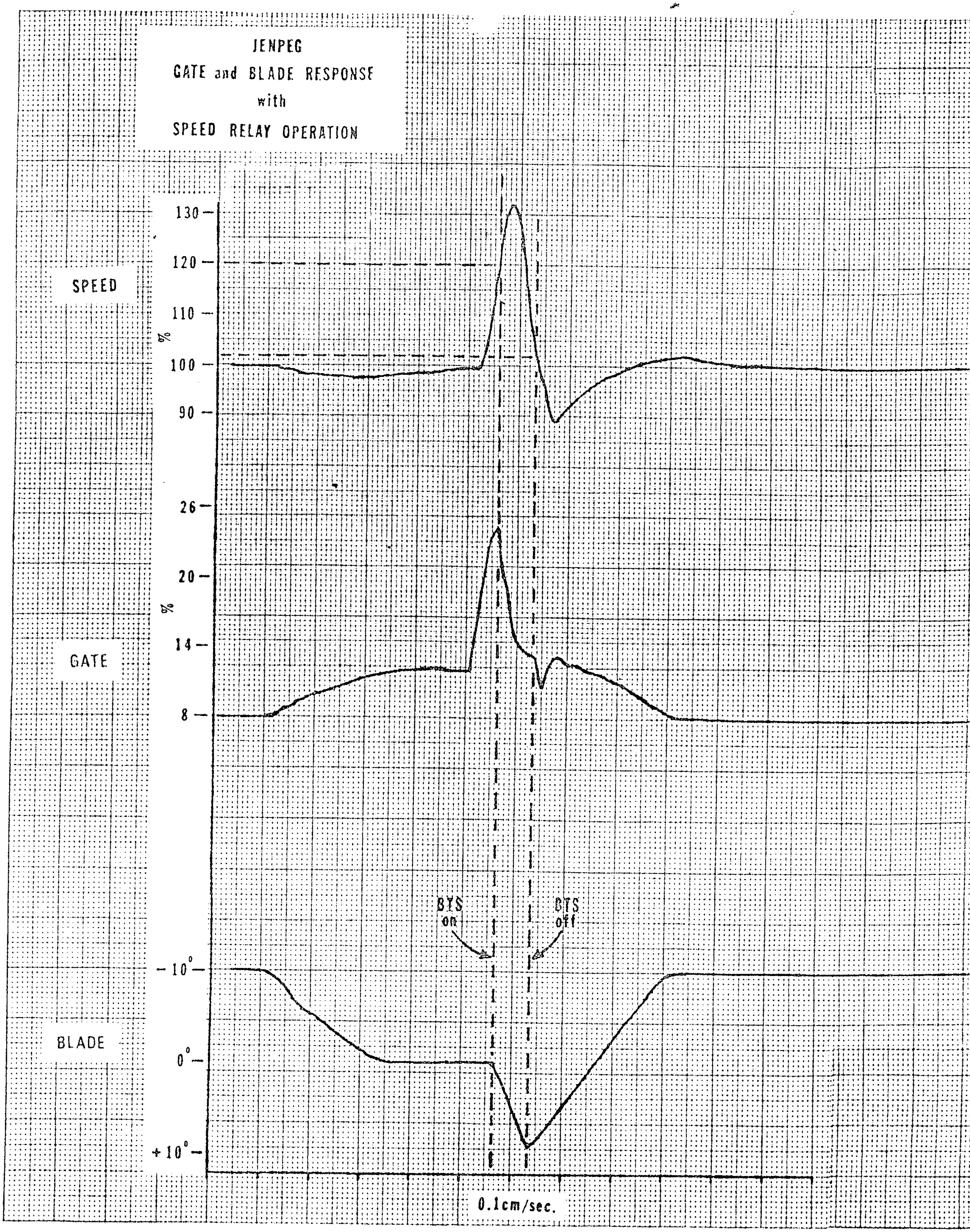


FIGURE 4.2 (d)

SIMULATION OF LOAD REJECTION AT SPEED NO LOAD and are shown in Figure 4.2 (d). The successful completion of these tests and adjustment of governor parameters means that the unit is ready for synchronization to the system.

4.4 On Line Response to Load Command Signals

Once the governor response is checked, the unit can be synchronized to the system. The response of the unit to load command signal is determined by generating a load command signal by adjusting the load adjust setter. The gate opening and blade angle traces recorded during various modes of operation, defined below, are presented in Figures 4.3 (a) to 4.3 (e).

i) Unit start up to speed no-load, synchronizing and loading

ii) Load changes in 5% steps

iii) Slow uninterrupted loading and unloading

iv) Fast uninterrupted loading and unloading

Figure 4.3 (a) shows the gate position and blade angle traces obtained for unit start to speed no-load, synchronization and unit loading. Gate position and blade angle traces recorded during 5% load step increases and decreases are shown in Figure 4.3 (b) and 4.3 (c). Gate position and blade angle obtained during uninterrupted slow and fast loading and unloading of the unit are given in Figures 4.3 (d) and 4.3 (e). These tests will indicate if there are any oscillations at a particular gate opening which may require a change in governor adjustments.

4.5 Governor Operation During Load Rejection

The speed of the unit increases following load rejection, a signal to lower speed is generated in electrical part of the governor and is

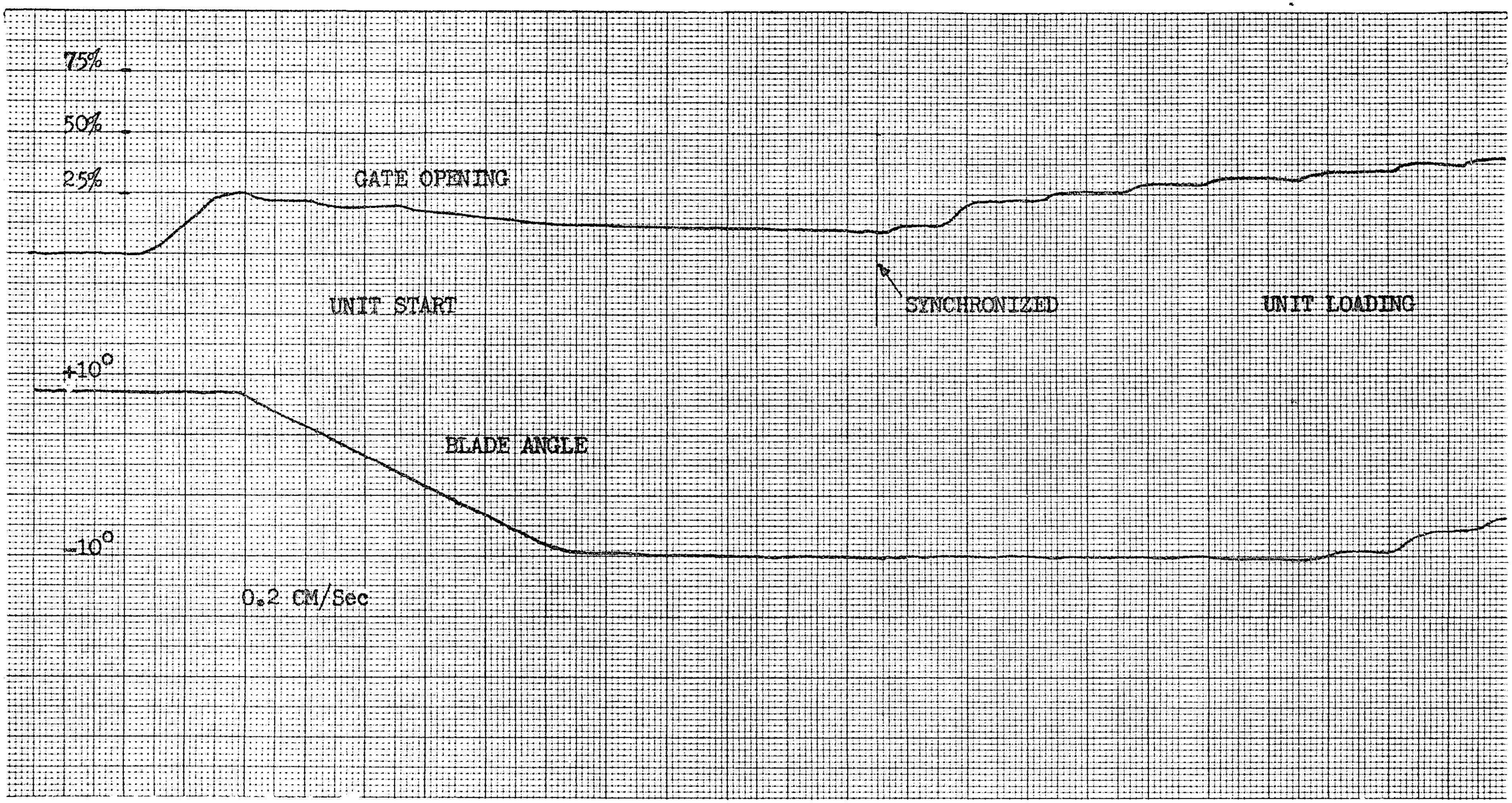


FIGURE 4.3 (a)

GATE POSITION AND BLADE ANGLE TRACES OBTAINED FOR
UNIT START TO SPEED NO-LOAD, SYNCHRONIZATION AND LOADING

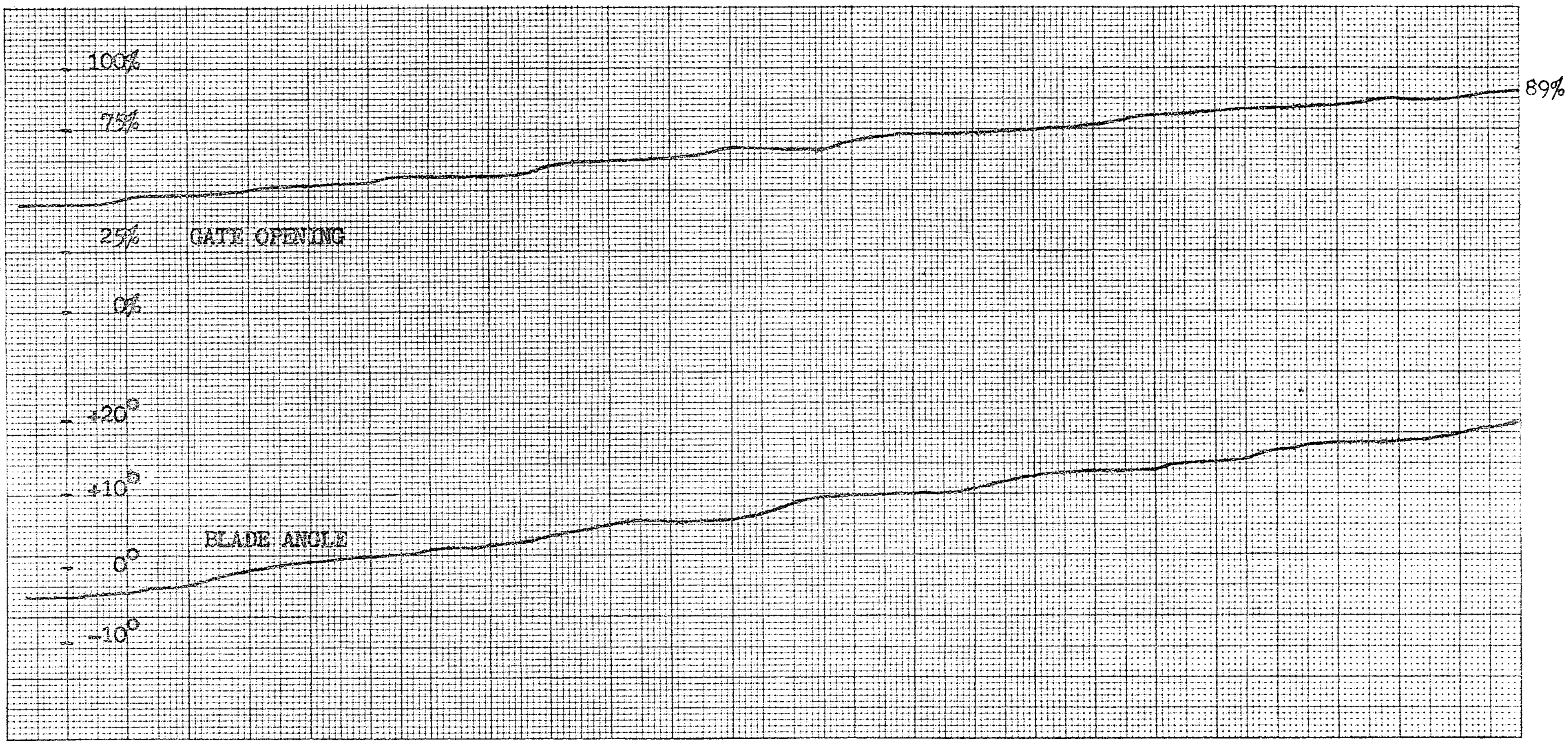


FIGURE 4.3 (b)

GATE POSITION AND BLADE ANGLE TRACES
OBTAINED DURING LOAD INCREASE IN 5% STEPS

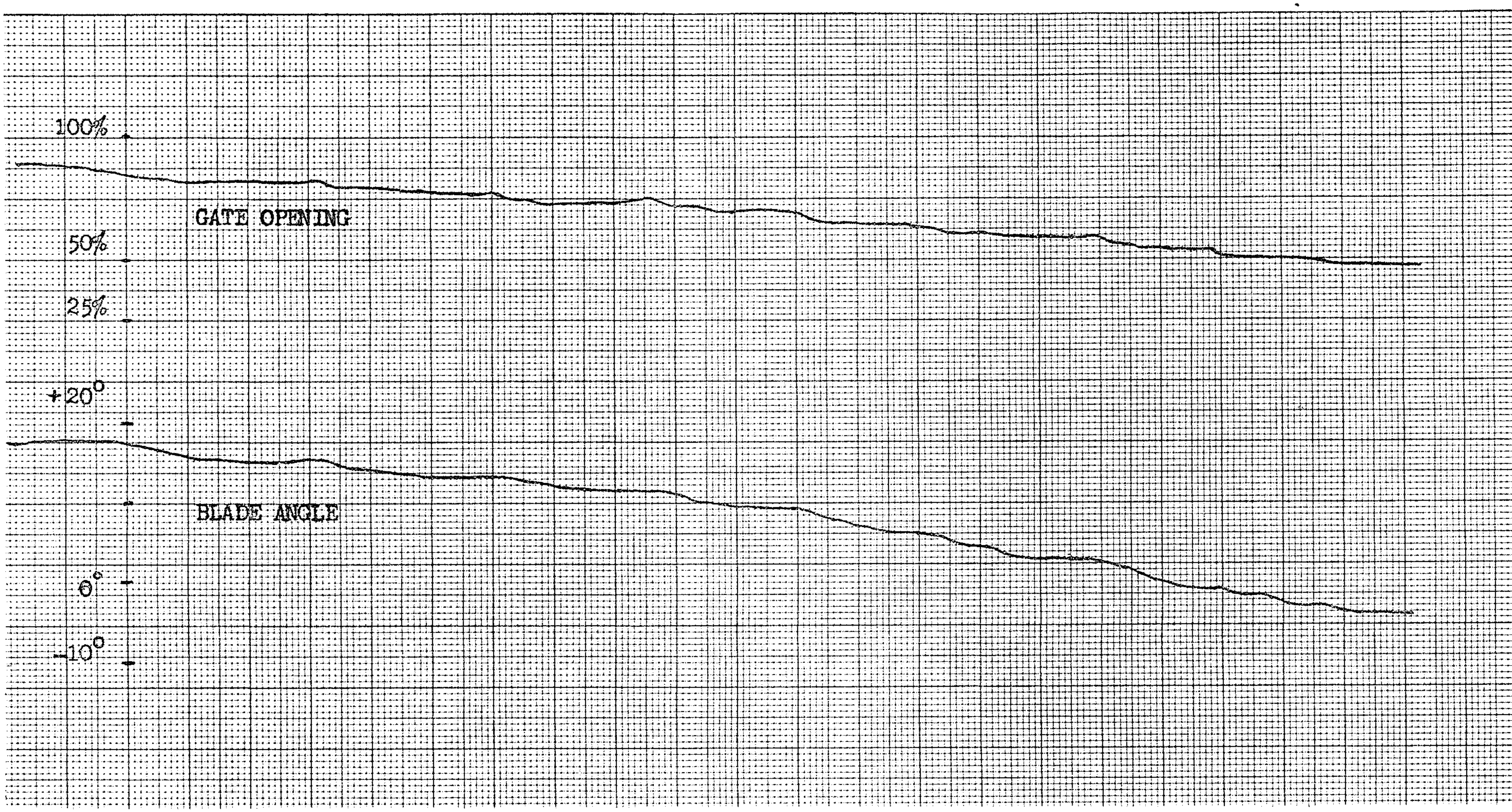


FIGURE 4.3 (c)

GATE POSITION AND BLADE ANGLE TRACES
OBTAINED DURING LOAD DECREASE IN 5% STEPS

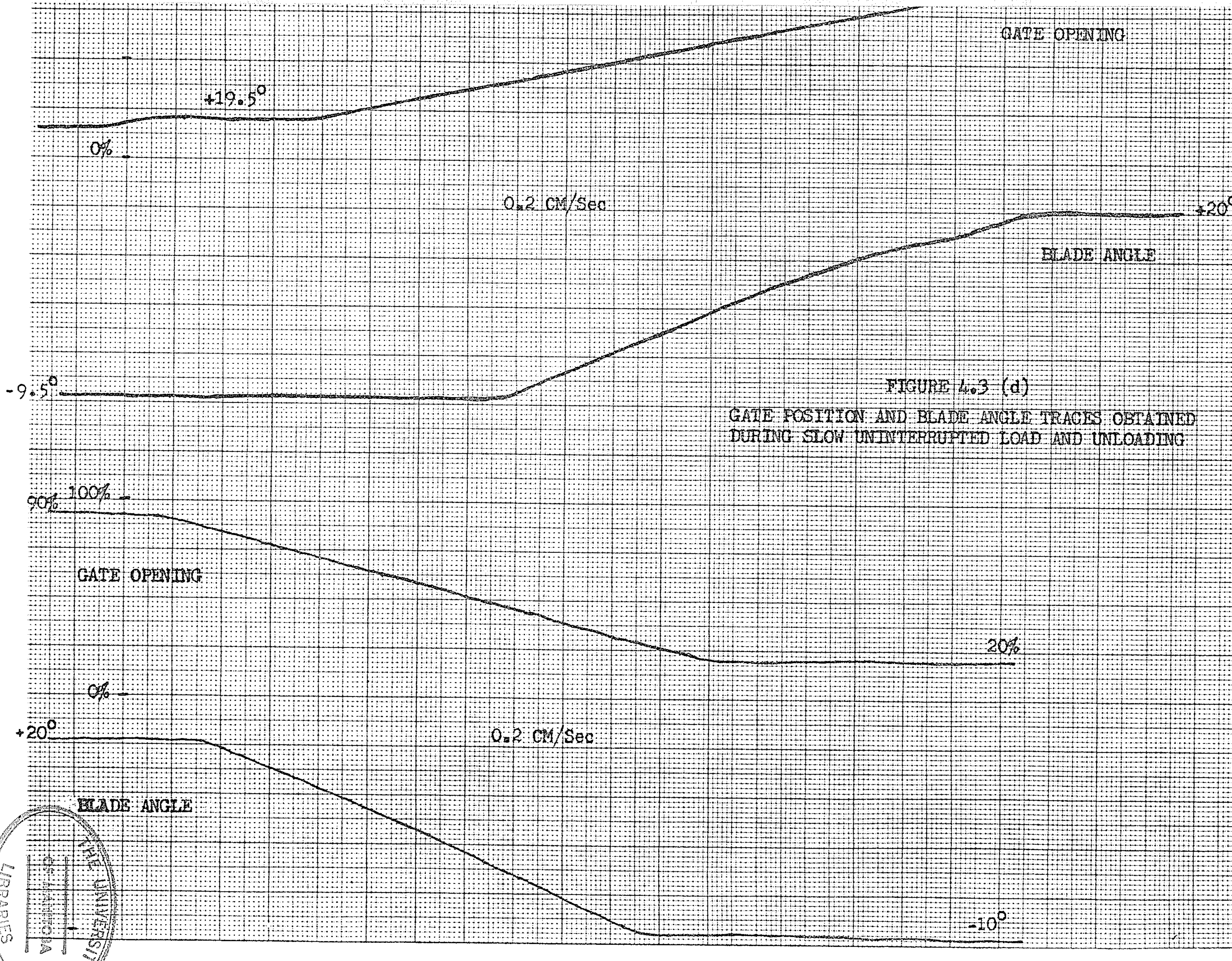


FIGURE 4.3 (d)

GATE POSITION AND BLADE ANGLE TRACES OBTAINED DURING SLOW UNINTERRUPTED LOAD AND UNLOADING

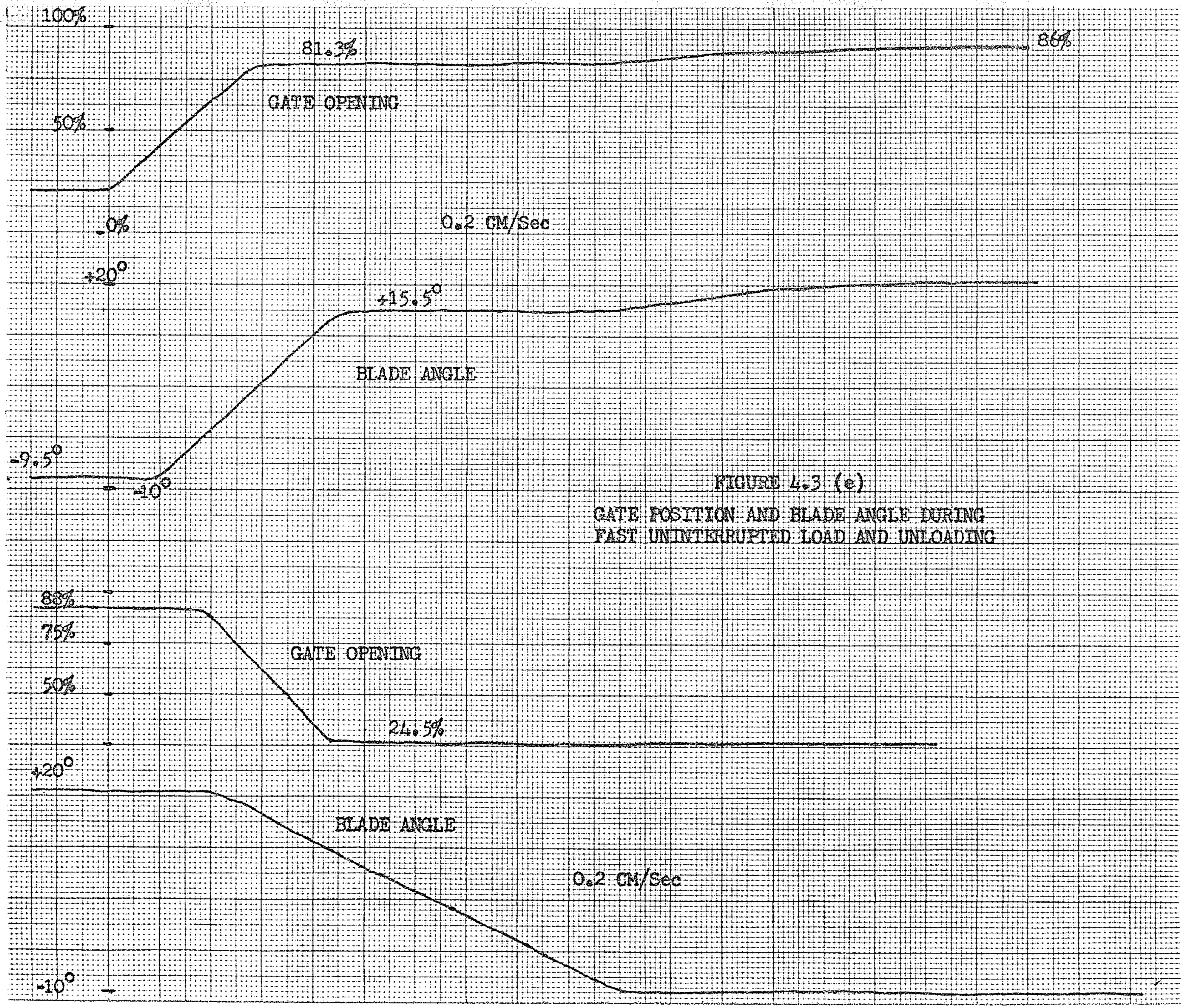


FIGURE 4.3 (e)

GATE POSITION AND BLADE ANGLE DURING FAST UNINTERRUPTED LOAD AND UNLOADING applied to the transducer coil to close wicket gates.

When unit speed reaches 115% of rated, blade tilt solenoid is energized and programmed closing mechanism functions to bring unit speed to 100%. Wicket gates are closed to a position equal to or less than the start opening gate position. The control of wicket gates from electro-hydraulic transducer is disconnected at 115% speed and upon energizing the blade tilt solenoid, the blade tilt mechanism operates and adjusts the blade angle to starting angle and is known as blades are 'OFF CAM'.

The wicket gates and starting blade angle remain held until the unit deccelerates to the rated speed at which time blade tilt solenoid is de-energized. The unit speed control is transferred over to governor through electro-hydraulic transducer and wicket gate changes to speed no-load opening position and blade tilt mechanism is released so that blade angle control is placed 'ON CAM'.

4.5.1 Hard Shutdown

This is a type of load rejection when the load is disconnected from the unit and this results in turbine wicket gates closing to zero and the blade angle moves to starting angle. The unit overspeeds first then speed decreases and the unit comes to complete stop. Hard shutdown takes places for a fault within the unit, for example:

i) excitation system faults

ii) generator faults

iii) governor faults

iv) prime mover faults

Under these conditions the unit is shutdown by the governor. If for some reason the governor fails to close the wicket gates and shutdown the unit, the unit speed will increase and overspeed protection operates to bring down the head gates. At Jenpeg Generating Station there are no head gates provided for overspeed protection of the unit. The unit is designed to sustain runaway speed for a few hours which will be required to place the stop logs in the intake passage. At Jenpeg the hard shut-down can take place under the following two conditions:

a) The governor closes the wicket gates and brings the unit speed to zero.

b) The emergency valve operates and closes the wicket gates and by-passes the governor actuator.

Each of these conditions will result in different gate, blade angle and speed characteristics.

4.5.1.1 Governor Control and Protection

Whenever the unit is required to be shutdown due to a fault, the generator breaker will open by protection and a load rejection will take place. As the unit speed increases, the speed error signal will operate through the transducer to close the wicket gates. As the speed increases to 115%, the blade tilt solenoid will energize, which in turn will close the wicket gates to a position selected for the programmed closing. The blade angle also changes to the starting angle. The gates will close at the maximum rate of gate closing determined by the gate timing adjustment. This is the normal operation of the governor during hard shutdown for vertical type units. At Jenpeg Generating Station this mode of operation for the governor is not used due to possible water hammer problems on the tailrace side of the unit. It is thought that water hammer will occur if the wicket gates close at the maximum rate because the water flow will be suddenly stopped. Therefore no-load rejection tests (hard shutdown) under governor control have been carried out to avoid counter thrust on the bearing. A modified mechanism to shutdown the unit to zero speed is used which is explained in the next section.

4.5.1.2 Emergency Gate Closing Valve

Normally the emergency gate closing valve will be used if there is a failure in the actuator. It is intended to close the wicket gates under this condition. The actuator failure is sensed by monitoring the position of the distributing valve when the unit speed increases to 115%. Upon failure of the actuator the emergency gate closing valve is energized and governor oil under pressure is directly applied to the closing side of the gate servomotor. The wicket gates are closed and the unit is brought down to zero speed. This is similar to head gates trip on conventional vertical type turbine units. Head gates will drop if the unit speed reaches the overspeed trip setting. In most cases this will happen only if the governor did not operate correctly. A number of operations of emergency gate closing valve at 25%, 50%, 75% and 100% wicket gate opening were carried out. The unit speed, gate opening and blade angle recorded during these tests are reported in Appendix D.

Once the emergency gate closing valve is energized, the wicket gates close at a lower gate closing rate to a pre-adjusted gate opening normally 30%, when programmed closing mechanism takes over. This programmed closing mechanism is different from the one which is energized by the blade tilt solenoid and was explained in section 3.4.5. The emergency programmed closing slows the rate of gate closing thereby reducing the possibility of water hammer.

Figure 4.4 (a) shows the speed response following a hard shutdown by the use of the emergency gate closing valve from 7, 14, 28 and 30.8 mW output levels.

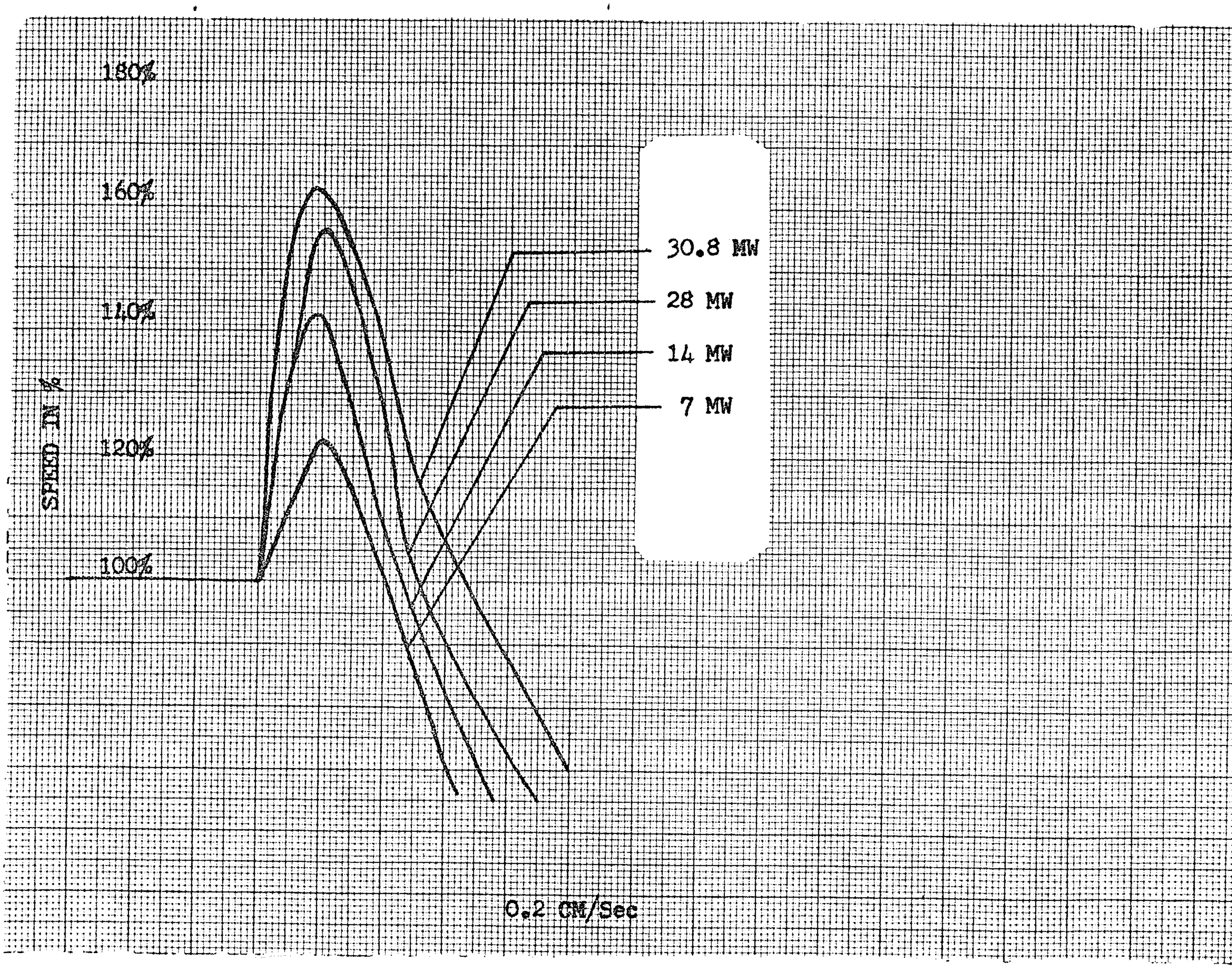


FIGURE 4.4 (a)

SPEED RESPONSE CHARACTERISTICS FOR 7, 14, 28 AND 30.8 MW LOAD REJECTION (HARD SHUTDOWN) BY EMERGENCY SLIDE VALVE OPERATION

4.5.2 Soft Shutdown

This is the type of load rejection when the load is disconnected from the unit and this results in overspeed and the unit speed returns to rated value under governor control. The unit speed does not drop to zero following loss of load. This may be the result of a fault on the transmission network interconnecting the unit to the power system or any other operation which isolates the unit from the system. For all these faults it is intended to keep the unit running and speed is brought down to speed no-load under governor control. These conditions are simulated by opening the generator breaker and gate opening, blade angle and unit speed is recorded and are shown in Figures 4.5 (a) to 4.5 (d). It can be seen that the response is a function of various gain setting and adjustment of various mechanism. Load rejections were carried out at 25%, 50%, 75% and 100% load values. The results are reviewed to check the maximum overspeed value and the speed response whether it is stable following each load rejection. A number of adjustments were made to gain values and other mechanisms in the governor and series of load rejections tests were carried out. These test results are given in Appendix E.

A brief outline of various adjustments of these mechanisms is given here.

4.5.2.1 Governor Control with Speed No-Load Solenoid

Normally speed no-load solenoid limits the maximum gate opening when the unit is not synchronized to the system. Under this condition the speed no-load solenoid is energized and this is controlled by an auxiliary contact of the generator breaker. In most cases generator breaker opens and load rejection takes place and the generator speed is brought down to rated speed under governor control. The effect of adjustment of gate opening limit by speed no-load solenoid on the speed response of the unit is also studied and is reported in Appendix E.

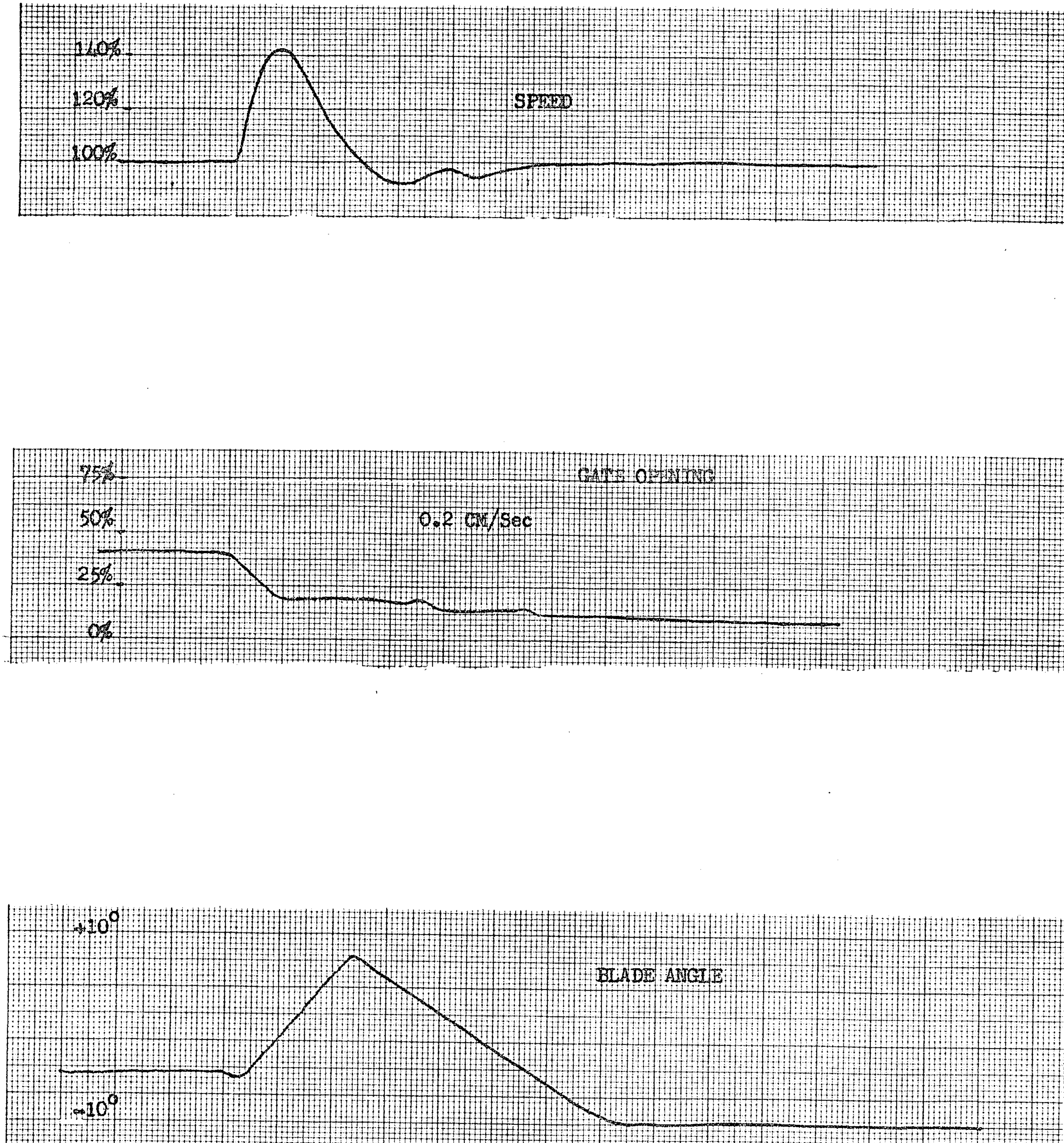
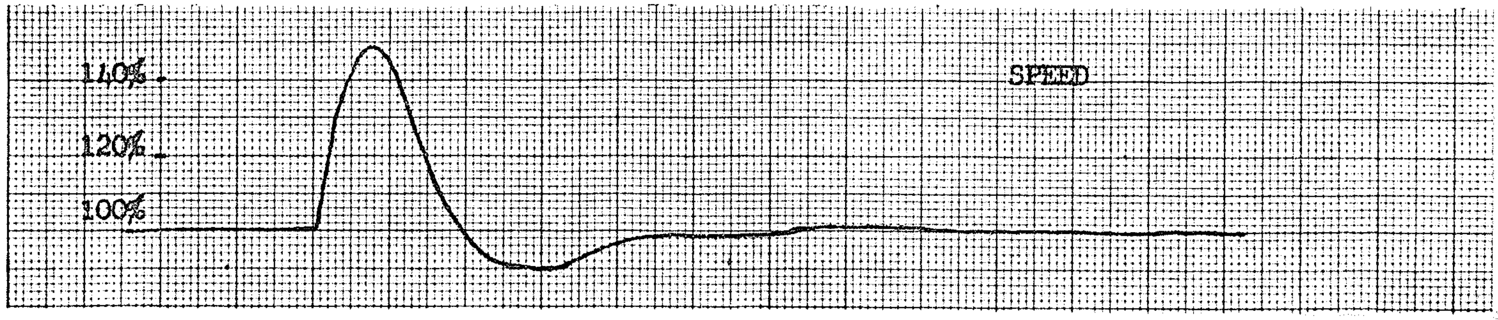
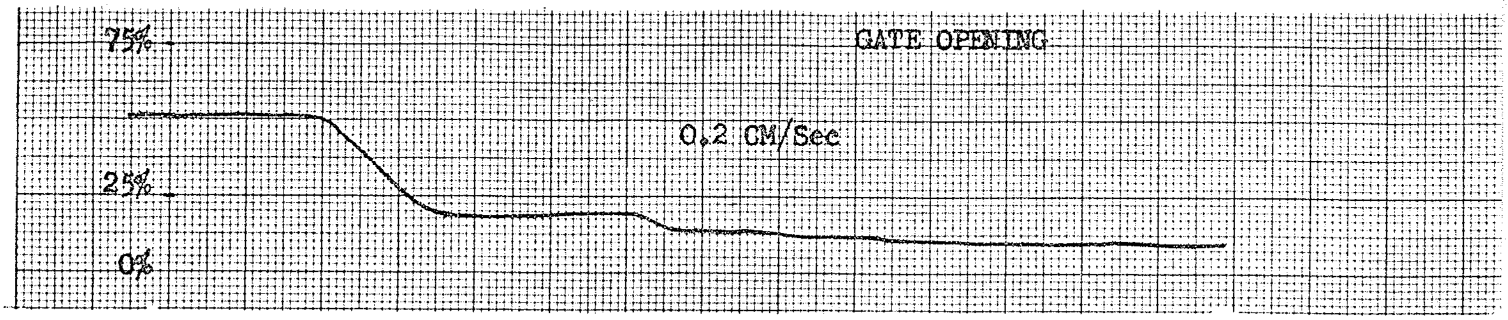


FIGURE 4.5 (a)

GATE OPENING SPEED AND BLADE ANGLE RECORDED
FOR 14 MW LOAD REJECTION SOFT SHUTDOWN





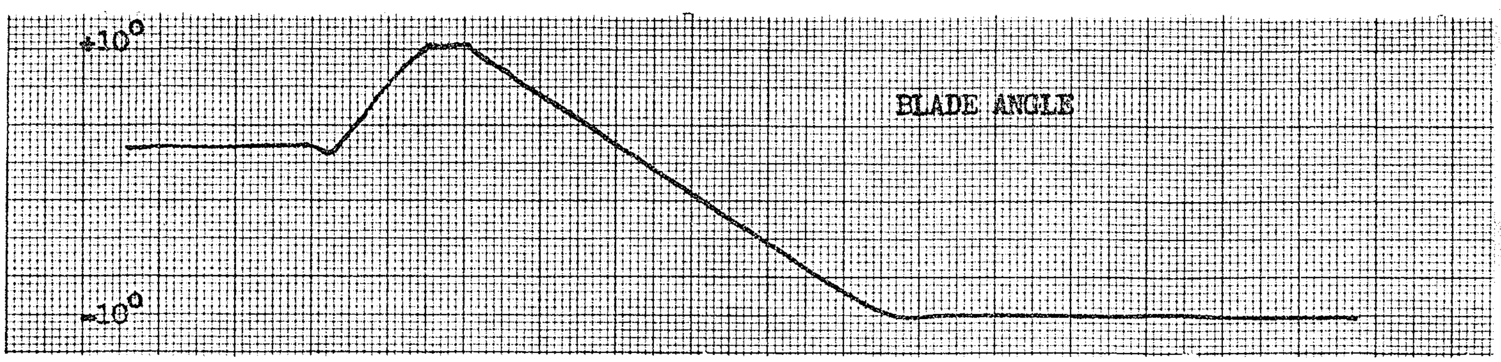


FIGURE 4.5 (b)

GATE OPENING, SPEED AND BLADE ANGLE RECORDED
FOR 21 MW LOAD REJECTION SOFT SHUTDOWN

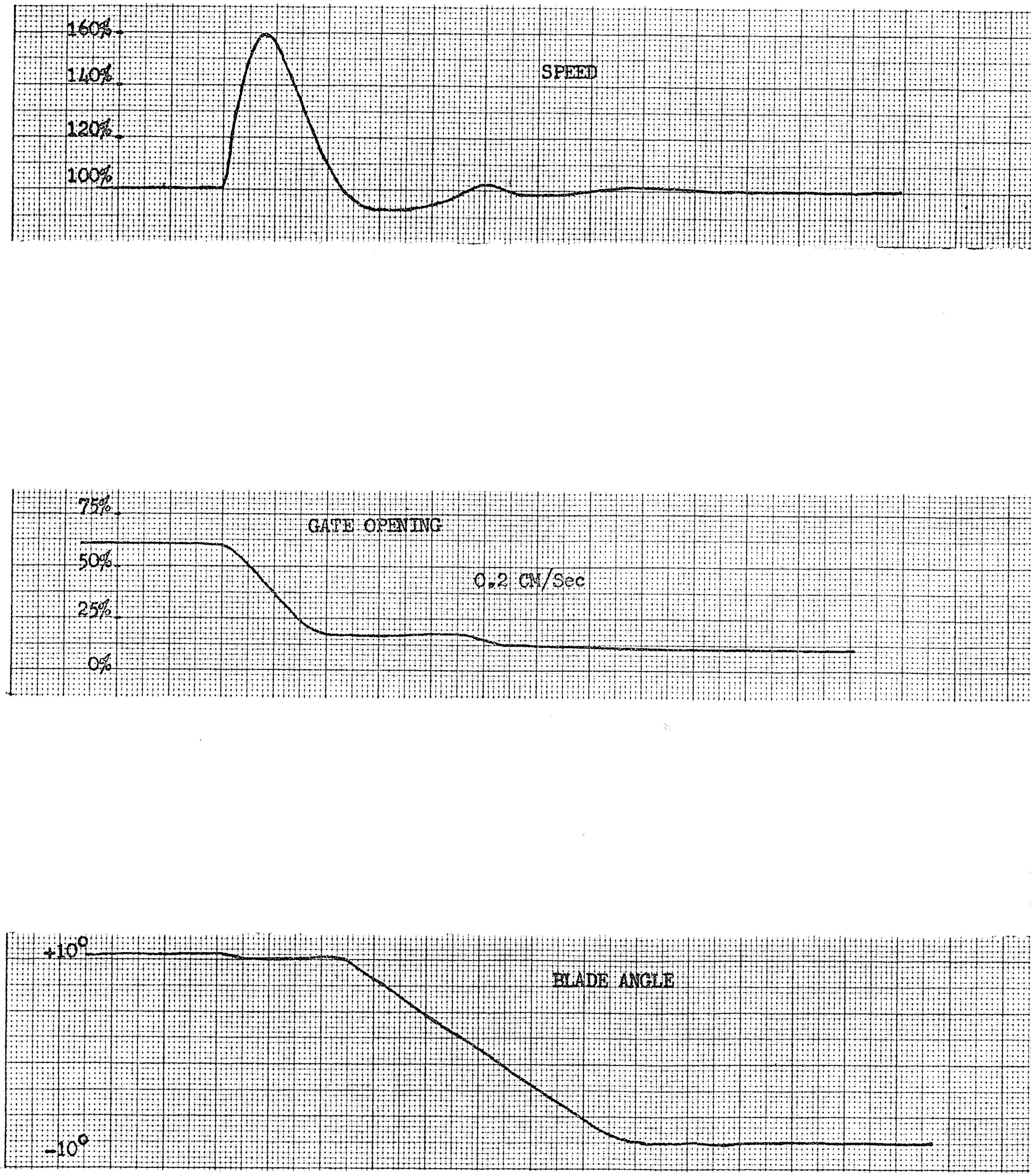


FIGURE 4.5 (c)

GATE OPENING, SPEED AND BLADE ANGLE RECORDED
FOR 28 MW LOAD REJECTION SOFT SHUTDOWN

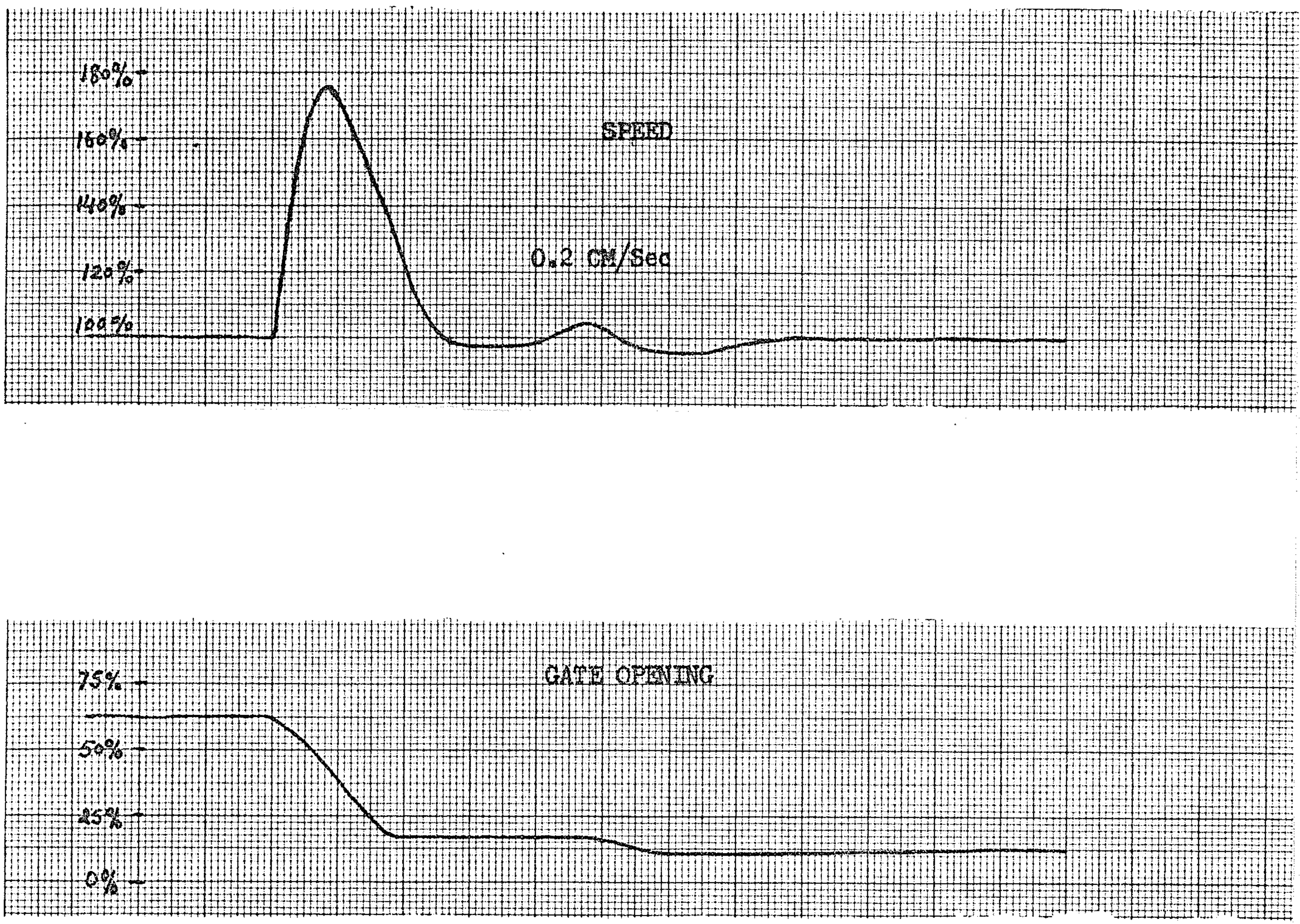


FIGURE 4.5 (d)

GATE OPENING AND SPEED TRACES RECORDED
FOR 30.8 MW LOAD REJECTION SOFT SHUTDOWN

4.5.2.2 Governor Control without Speed No-Load Solenoid

In few cases the generator breaker may not open although the load has been removed from the unit. This can be as a result of a disturbance on the system which results in the opening of transmission line breaker at the far end of the line. Under this condition the speed no-load solenoid remains de-energized and results in no limit for gate opening due to speed no-load solenoid. This condition is simulated while carrying load rejection tests and its effect on speed response is determined. Test results are reported in Appendix E.

4.5.2.3 Programmed Closing Control

This mechanism has quite an effect upon the speed response of the unit following a load rejection. Blade tilt solenoid controls the operation of this mechanism. The blade tilt solenoid is energized whenever the unit speed increases to 115%-120% and de-energizes when the unit speed drops between 98% and 100%. This is the time duration when the programmed closing control effects the speed response of the unit. When blade tilt solenoid is energized the programmed closing mechanism will close the wicket gates to a pre-adjusted gate opening and blade angle is changed to blade angle adjusted for unit starting. The effect of programmed closing mechanism depends upon the following adjustments:

i) Unit speed when programmed closing mechanism begins

ii) Unit speed when programmed closing mechanism stops

iii) Starting blade angle in degrees

iv) Programmed closing gate opening

A number of load rejections were carried out for various adjustments of programmed closing mechanism and the test results obtained are reported in Appendix E. It can be seen that when unit speed drops to rated speed, blade tilt solenoid is de-energized, the speed is controlled by governor by using speed error signal. The wicket gates are not at speed no-load position and blade angle control is transferred to 'ON CAM'.

4.6 Normal Unit Shutdown

For normal operation, the operator should be able to start, synchronize and load the unit. This has been covered in the earlier sections. Once the unit is carrying load and is required to be shutdown by the operator either from remote or local control, the operator initiates the shutdown and the following sequence of events take place:

i) Unloading selsyn is energized to close the wicket gates to the speed no-load gate opening.

ii) When the unit output drops to zero, the unloading selsyn is de-energized.

iii) The generator circuit breaker opens at approximately no-load and the shutdown solenoid is energized, thus causing the wicket gates to fully close through the operation of mechanical mechanism in the actuator.

iv) At approximately 5% gate opening the blades are set to the starting blade angle.

The unit comes to complete stop and is now ready to be started and synchronized to the system and to pick up load.

It should be noted here that the operation of the unit governor during normal shutdown initiated by the operator is quite different compared to either hard shutdown or soft shutdown discussed in the earlier sections.

5. CONCLUSIONS

A general review of speed control of generators driven by hydraulic turbines and the use of various types of governor equipment has been carried out. The significant differences between various types of governors have been discussed. The proper operation of governors in a power system is quite important. The necessary tests to check the performance of the unit and adjustments of various parameters and their effect on speed response of the unit are reported.

The speed rise following a load rejection of bulb type horizontal units is higher than vertical type units. This is due to low inertia of the generator and turbine combined. Therefore governor adjustments are made to limit overspeed and to achieve stable response when speed is returning to rated speed. Although the gate time and blade time adjustments determine the maximum rate of gate and blade angle changes and has a most significant effect upon the speed response of the unit, these adjustments are made when the unit is de-watered. The adjustment of temporary droop, permanent droop, dashpot time constant and acceleration time constant are made during governor response tests at speed no-load. These adjustments can be changed even when the unit is on line. Generally these adjustments are made at speed no-load.

It has been shown that the following adjustments also effect the speed response of the unit under study:

i) The speed setting value at which blade tilt solenoid picks up and drops out. This in turn initiates programmed closing mechanism.

ii) Starting blade angle in degrees.

iii) Gate position setting for programmed closing.

iv) Speed no-load (starting) gate opening limit.

v) Gate position switch setting when speed no-load solenoid is energized.

A series of field test results were obtained for various combinations of these settings. It can be seen that a very judicious field test program is necessary to determine the optimum settings for all these adjustments to obtain satisfactory speed response. During these tests a number of other parameters are also recorded to check the effect of operation of the unit upon these parameters. For example, shaft run out's, water pressure downstream and upstream, bearing run out's, excitation system parameters, etc.

The effect of various gain values and other adjustments upon the speed response of the unit following load rejection have been reported in the previous chapters. The most sensitive gain adjustment is found to be acceleration time constant T_n. A larger value of T_n results in an oscillatory response. Temporary droop B_t and dashpot time constant T_d are adjusted to provide a damped response. The effect of additional adjustments available as listed previously is also quite significant as can be seen from load rejection test results. The importance of field test program for proper adjustment of governor system has been demonstrated.

A further work can be carried out by a computer simulation of this problem to determine the governor settings for a desired speed response and results compared with field data. The effect of various combinations of gain settings on the speed response of the unit can also be studied by computer simulation. The difference between field test results and computer simulation study results can also be analyzed.

The purpose of this project report as outlined earlier has been completed and a scope for further work has been included. It has been demonstrated that a series of tests are necessary to arrive at a final set of adjustments to achieve a desired speed response of bulb type units when subjected to sudden load changes.

6. REFERENCES

1. L.M. Hovey, "A Study of Governors and Their Adjustment on the MANITOBA HYDRO-ELECTRIC BOARD SYSTEM", Presented to CEA, Winnipeg, March, 1959

2. S.X. Casacci, E.E. Chapus, "The Bulb Turbine", A.S.M.E. 64-WA/FE-27

3. C.L. Avery, "Field Adjustment of Hydraulic Turbine Governors", A.S.M.E. Paper No. 59-A-108, December 1959

4. L.M. Hovey, "Optimum Adjustment of Governors in Hydro Generating Stations", The Engineering Journal, Engineering Institute of Canada, Montreal, Quebec, Canada, November, 1960

5. H. Schiott, "Optimum Setting of Water Turbine Governors", Transactions, The Society of Instrument Technology, London, England, 1960

6. L.M. Hovey, L.A. Bateman, "Speed Regulation Tests on a Hydro Station Supplying An Isolated Load", Trans. AIEE (Power Apparatus and Systems), Vol 81, pp 364-368, October 1962

7. D.A. Sheare, M.M. Uloth, H.H. Warnock, "Bulb Turbine Generators for Jenpeg Generating Station", Presented to 89th Annual Congress, Engineering Institute of Canada, Winnipeg, October, 1975

8. G.S. Hope, O.P. Malik, A.S.A. Farag, "Analysis of a Real Time Digital Governor", A 76 092-7 IEEE PES Winter Power Meeting and Tesla Symposium, New York, N.Y., January 25-30, 1976

9. O.P. Malik, G.S. Hope, A.S.A. Farag, "Design and Test Results of a Real Time Digital Governor", A 76 111-5 IEEE PES Winter Power Meeting and Tesla Symposium, New York, N.Y., January 25-30, 1976

10. G.A. Jablonski, "First of Six Bulb Turbines Produce Power at Jenpeg", Modern Power and Engineering, November, 1977

11. Operation and Maintenance Manuals for Jenpeg Generating Station of Manitoba Hydro by Leningrad Metal Works, U.S.S.R.

12. W. McGillvery, M.M. Uloth, "Features of Manitoba Hydro's Jenpeg Generating Station", Paper Presented at IEEE PES Winter Power Meeting New York, N.Y., February 4-9, 1979

APPENDIX A

The most commonly used terms during the study of governor systems are defined and a method to determine some of the parameters are presented under the following headings:

i) Glossary of Terms

ii) Restoring Ratio

iii) Temporary Droop and Dashpot Constant

iv) Calculation of Water Starting Time

v) Measurement of Temporary Droop

vi) Calculation of Mechanical Starting Time

vii) Calculation of Change of Speed Due to Load Rejection

(i) GLOSSARY OF TERMS

1. Acceleration - Rate of change of speed with respect to time; usually expressed in terms of percent per second.

2. Compensation - A modification of the gate motion introduced to prevent overtravel of the gates and thus produce stability. Compensation in a governor produces transient (temporary) speed droop.

3. Dead Band - Total magnitude of the sustained speed change within which there is no resulting measurable change in the position of the turbine gates.

4. Hunting - A rhythmic variation of speed which can be eliminated by blocking the governor with load gate limit but which will re-appear when control is returned to the governor.

5. Isochronous-Constant Speed - Specifically the same average speed regardless of load.

6. Prime Mover - A device which converts energy in its natural state into mechanical or electrical power.

7. Sensitivity - The smallest speed change for which the governor will make a change of energy medium.

8. Speed Regulation - A decrease in speed as the load is picked up by the prime mover from no load to full load without manually changing speed setting. It may be expressed in rpm or percentage, or may be shown graphically as a curve relating steady state output to speed.

9. Stability - The capability of the governor system to position the gates so that sustained oscillations of turbine speed or output are not produced by the governor system during operation under sustained load demand or following a change to a new sustained load demand. Forced oscillations of the governor system introduced to reduce friction are excluded.

10. Load Feedback - The feedback of a signal linearly proportional to generator output.

11. Speed Signal Generator-S.S.G. - A device driven by the generator shaft which produces a voltage pulse whose frequency is proportional to unit speed.

12. L.V.D.T. - A feedback transducer for the pilot servo displacement and is a low voltage displacement transducer.

13. Transducer - Any device which changes the electrical signal to a corresponding mechanical position.

14. Speed Sensor - Converts the voltage pulse from the S.S.G. into an electrical error signal using the unit speed adjustment as an adjustable reference.

15. Speed Reference - The speed setting which the speed sensor refers to in determining an offspeed condition.

16. Hydraulic Amplifier - Increases the hydraulic power.

17. Joint Load Equalization - Each unit under joint control operation will automatically assume an equal share of load to maintain the station generation as set by the master station megawatt control within the available capacity of the unit regardless of:

    a) Changes in net head
    b) Restriction of water flows
    c) The addition or subtraction of independently operated or participating units from the system

18. Hydraulic Turbine - A hydraulic turbine is a prime mover consisting essentially of a runner connected to a shaft, a mechanism for controlling the quantity of water, and water passages to and from the runner.

19. Turbine Classes - Modern hydraulic turbines are divided into three classes:

a) Impulse Turbine - An impulse turbine is one having one or more free jets discharging into an aereated space and impinging on the buckets of the runner, a means of controlling the rate of flow, a housing and a discharge passage. The water supplies energy to the runner in kinetic form.

b) Reaction Turbine - A reaction turbine is one having a water supply case, a mechanism for controlling the quantity of water and for distributing it equally over the entire runner intake, and a draft tube. The water supplies energy to the runner partly in kinetic and partly in pressure form. There are three principal types of reaction turbines as follows:

i) Francis Turbine

ii) Adjustable-Blade Propeller Turbine (Kaplan)

iii) Fixed-Blade Propeller Trubine

c) Bulb Type Units - A bulb turbine is a horizontal Kaplan located in the water flow stream. The turbines and generators have horizontal shaft arrangement and the bulb is completely submerged in water. The wicket gate and runner chambers are exposed to the turbine pit to enable the removal of turbine components without disturbing the generator. A passage way between the two ends of the bulb is provided through the supporting pedestal. The water passage is hydro dynamically superior to vertical units because of no spiral cases and change of direction of water passage.

20. Penstock - A closed supply passage extending from the surge tank to the turbine case or from the forebay if a surge tank is not used.

21. Gate Lock - A device to lock the wicket gates in a given position with sufficient strength to resist the full force of the servomotor.

22. Cushion Device - A means of retarding the rate of movement of the servomotor piston near the closed position.

23. Relief Valve - A valve which automatically relieves excessive pressure in the governing system.

24. Accumulator - A reservoir containing oil and air under pressure for use in the governing system.

25. Sump Tank - A reservoir for the exhaust oil from governing system.

26. Shutdown Mechanisms - A device for shutting down the turbine by remote control.

   a) Complete Shutdown Solenoid - Closes the gates when one or more protective devices function.

   b) Partial Shutdown Solenoid - Closes the gates to a predetermined opening when one or more protective devices function.

   c) Reset Mechanism - A device to reset or release the shutdown mechanism.

   d) Automatic Start-Stop - A device by means of which the unit may be started and stopped by remote control.

27. Ballhead - A speed-sensitive element producing a mechanical movement which is a function of the change in speed.

   a) Flyballs or Flyweights - Weights mounted in such a manner as to form a rotating pendulum which is sensitive to speed change.

28. Relay Valve or Distributing Valve - A valve positioned by a servomotor controlled by the pilot valve. It controls the flow of oil or other media, which, in turn, operates the turbine-flow control mechanism.

   a) Stops - Adjustable blocks which limit the distributing valve travel and so determines the minimum governor time or the most rapid rate at which the governor servomotor piston can travel. Stops are designated as opening or closing stops depending on whether they limit the opening or closing time.

29. Pilot Valve - A small valve actuated by low force level signals and designed to handle a relatively small flow of oil. It responds to the mechanical movements of the governor head and, by controlling the movement of the valve servomotor, controls the movement of the distributing valve.

30. Dashpot - Introduced in the compensating mechanism in such a manner as to produce the desired stabilizing effect.

31. Servomotor - A hydraulic cylinder and piston assembly controlled by the pilot valve (acting through the valve servomotor) and usually acting on the energy medium control.

32. Actuator - Hydraulic part of the governor that acts on a remote servomotor.

33. Governor Head Drive - The means used to rotate the governor head.

    a) Mechanical Drive - May be either through belts or gearing.

    b) Electrical Drive - May be either through potential transformers in the driven generator leads, or through an independent generator which is coupled to the main generator shaft and connected electrically to a motor driven governor head.

34. Restoring Mechanism - Those elements which transmit the servomotor movement to the governor mechanism to establish proportionality between the servomotor and the governor mechanism movements.

35. Compensating Mechanism - Modifies the gate movement to prevent overtravel, thus producing stability. It slows down and stops the correcting gate movement before the speed has returned to normal.

36. Manual Control - The means whereby the turbine-flow control mechanism may be operated manually and independent of the governor control.

37. Overspeed Switch - Operated at a predetermined overspeed of the unit to close the turbine gates and/or to sound an alarm.

(ii) RESTORING RATIO

The pilot valve is uncentred by:

(i) speed rod mechanism

(ii) change in speed setting

(iii) governor dashpot action

(iv) speed droop mechanism

This movement of the pilot valve is amplified as a movement of the distributing valve. Restoring ratio equals the amplification of the movement of pilot valve to result in a movement of distributing valve. Mechanical restoring ratio is shown in Figure A 1.

Physically it is a feedback across the distributing valve and pilot valve. It is normally referred to 30:1 or 20:1 ratio. The ratio of 30:1 means when pilot valve moves 0.01", the distributing valve moves 30 X 0.01" = 0.30" and then the pilot valve is centred. This centring of the pilot valve is caused by a mechanical linkage called Restoring ratio arm which has adjustments.

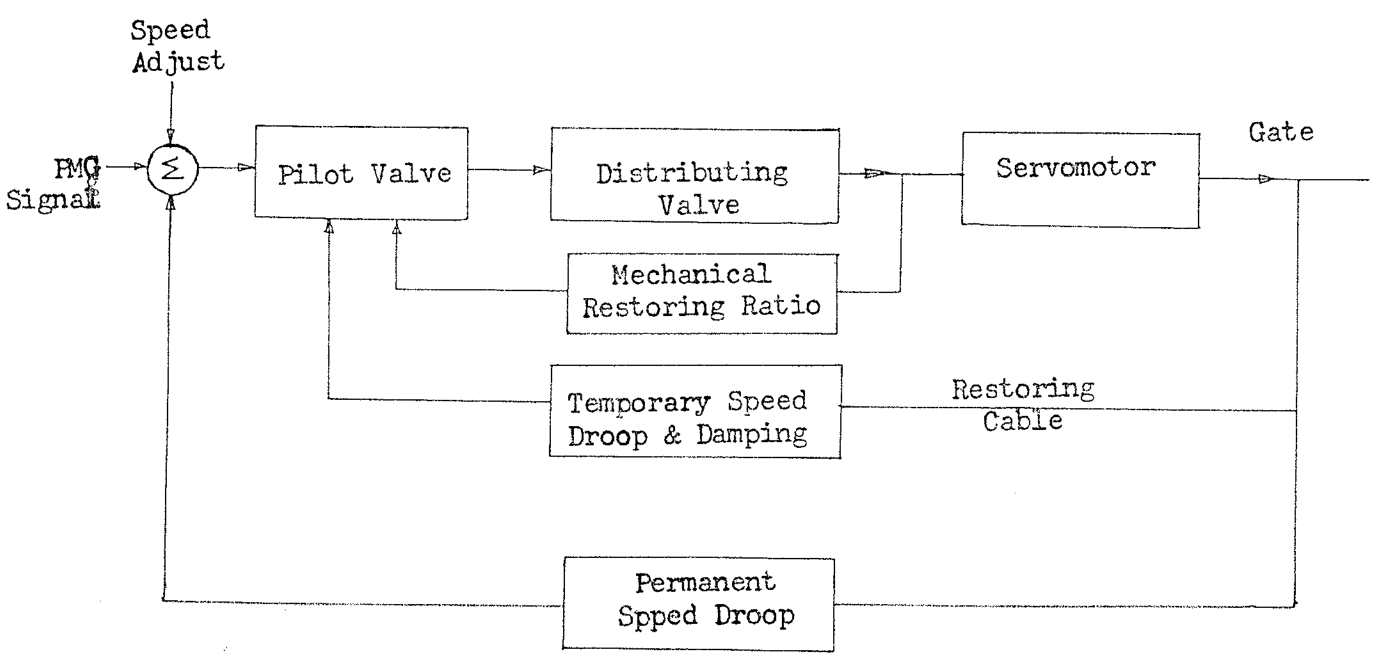


FIGURE A 1

GOVERNOR BLOCK DIAGRAM

(iii) TEMPORARY DROOP δ AND DASHPOT TIME T_d

Temporary droop is defined as per unit change in speed from zero gate to full gate with dashpot needle valve fully closed.

With small values of temporary droop the machine becomes unstable and oscillates about an average speed which is unacceptable operating condition.

The unit becomes quite stable if the governor with large temporary droop and with large dashpot time constant is used. Temporary droop effect slowly decreases with time dependent upon the setting of the dashpot needle valve.

Typical values of temporary droop are 0.2 to 0.8 pu.

Typical dashpot time constants are 2-30 seconds.

(iv) CALCULATION OF WATER STARTING TIME T_w

It is calculated by taking a numerical integration over the entire length of the water passage. Thus it can be defined as $T_w = \sum \frac{LV}{gh}$

Where: L = Incremental section of water passage in ft.
V = Velocity of water within that section in ft/sec.
g = Acceleration of gravity in ft/sec^2.
h = head in ft.

T_w is important because it has a direct effect on the stability of the hydraulic system.

For plants in service the T_w is effected by head and water velocity. The effect of head on T_w value can be derived as follows:

$$\frac{T_w^1}{T_w} = \frac{\sqrt{h}}{\sqrt{h^1}}$$

Normally T_w is in the order of 0.5 to 6.0 seconds.

For plants with surge tanks, the calculation of T_w is carried out from surge tank to the draft tube.

Surge tank acts like a temporary Forebay and has no effect on T_w value.

Example: T_w = 4.9 sec at 26' net head, i.e. 7.3 meters for Jenpeg Units.

For machines with short intake, an approximate value of T_w is given by $T_w = 3D/H$ seconds.

Where: D = Diameter of the runner in feet
H = Head in feet

(v) MEASUREMENT OF TEMPORARY DROOP δ

Run the unit at speed no load with governor in service.
Disconnect speed no load solenoid.

Depress gate opening by gate limit to decrease speed by 0.10 per unit, i.e. 10%. When the unit speed is stabilized, close the dashpot needle valve and record gate position. Remove governor limit, the wicket gates will suddenly open to a gate opening depending upon temporary droop setting. Read maximum gate opening.

The temporary droop $\delta = \frac{\Delta N}{\Delta G}$

Where: $\Delta N = 0.10$ pu, i.e. 10% speed change

$\Delta G = 0.55 - 0.35 = 0.2$ pu, i.e. 20% gate opening change

Measured temporary droop $\delta_m = \frac{0.10}{0.20} = 0.5$ pu, i.e. 50%

It is assumed in this method that the unit speed does not change appreciably during the gate transient. If δ_m is not correct value, then the compensating crank or the ratio of the upper floating lever or both are adjusted and the test is repeated until the correct value is obtained. When the lever has been changed by repinning in another hole the distributing valve must be recentred.

Once the measured temporary droop (δ_m) is known, the temporary droop for analysis or computer simulation can be calculated as follows:

δ temporary droop = δ_m (1 - SNL gate opening)

Say SNL gate opening = 0.35 pu, i.e. 35% Where SNL = speed no load

$$\delta = \delta_m(1 - 0.35)$$

$$= 0.5(0.65)$$

$$= 0.325 \text{ pu, i.e. } 32.5\%$$

When water starting time T_w and mechanical starting time T_m are known, the temporary droop, $\delta = 2.5 \frac{T_w}{T_m}$

(vi) CALCULATION OF MECHANICAL STARTING TIME T_m

Mechanical starting time may be defined as the time in seconds required to bring the machine from zero speed to rated speed with rated torque applied.

$$T_m = \frac{WR^2 \times (RPM)^2 \times 10^{-6}}{1.61 \times HP} \quad \text{seconds}$$

Where: WR^2 = Moment of inertia of generator rotor and turbine runner in lb ft^2

RPM = Rated speed of the machine

HP = Rated horsepower of turbine

In stability studies interia time constant H is used and is given by substituting KW for HP and dividing T_m by 2.

$$H = \frac{WR^2 \times (RPM)^2 \times 10^{-6}}{1.61 \times 1.34 \times KW} \times \frac{1}{2}$$

$$H = \frac{0.231 \times WR^2 \times (RPM)^2 \times 10^{-6}}{KW} \quad \text{seconds}$$

T_m value for Jenpeg Unit is 1.8 seconds.

N = 62.07 RPM

WR^2 = 28,400 lb ft^2

Output = 28.9 MW

Typical values of T_m are 1 to 10 seconds.

(vii) CALCULATION OF CHANGE IN OVERSPEED DUE TO LOAD REDUCTION

$$\Delta W = \frac{Pa}{2HN} \Delta t$$

where N = number of generators supplying system

H = Inertia constant of one generator on 100 MVA base (1 p.u. = 100 MVA) Units MW-Sec/MVA

Pa = Accelerating power after the disturbance in pu on 100 MVA base

ΔW = P.U. change in frequency (120 π radians per second base)

Δt = Change in time in seconds

$$\frac{\Delta W}{\Delta t} = \frac{Pa}{2HN}$$

$\frac{\Delta W}{\Delta t}$ in the limit becomes $\frac{dw}{dt}$

$$\frac{dw}{dt} = \frac{1}{60}\frac{df}{dt} = \frac{Pa}{2HN} \quad \text{(f in Hz)}$$

or

$$\frac{Pa}{N} = \frac{2H}{60}\frac{df}{dt}$$

Thus, by measuring $\frac{df}{dt}$, the p.u. power and per unit overload can be computed.

Suppose the maximum frequency occurs at 4 seconds and we want to limit this frequency to 64 Hz to prevent tripping.

$$\Delta W = \frac{64 - 60}{60} = \frac{1}{15} = 0.0667 \text{ p u}$$

$$\Delta W = \frac{Pa}{2HN} \cdot \Delta t$$

$$0.0667 = \frac{Pa}{2HN} \times 4, \quad \text{where } \Delta t = 4 \text{ seconds}$$

$$Pa = \frac{2HN \times 0.0667}{4}$$

If the load reduction is known, i.e. accelerating power then the change in overspeed can be calculated by application of the same equation as shown above.

APPENDIX B

TYPICAL INFORMATION FOR GOVERNOR SPECIFICATION

The three term governor shall provide for proportional, integral and derivative modes of control as defined in the following equation.

$$Y = \left(B_a + \frac{B_i}{S} + B_d S\right)(C - X - B_p Y)\ F_{(s)}$$

Where:

Y = relative servomotor stroke deviation

C = relative command signal deviation

X = relative generator speed deviation

B_p = Permanent speed droop

B_a = Proportional gain

B_i = Integral gain

B_d = Derivative gain

All on a per unit basis and $F_{(s)}$ represents the transfer characteristics of the remaining amplifying, stabilizing and hydraulic networks and S is the Laplace Operator.

Adjustable devices should be calibrated directly in terms of B_a, B_i and B_d respectively and each shall be individually and independly adjustable.

Also $B_a = K_1 \frac{T_m}{T_w}$

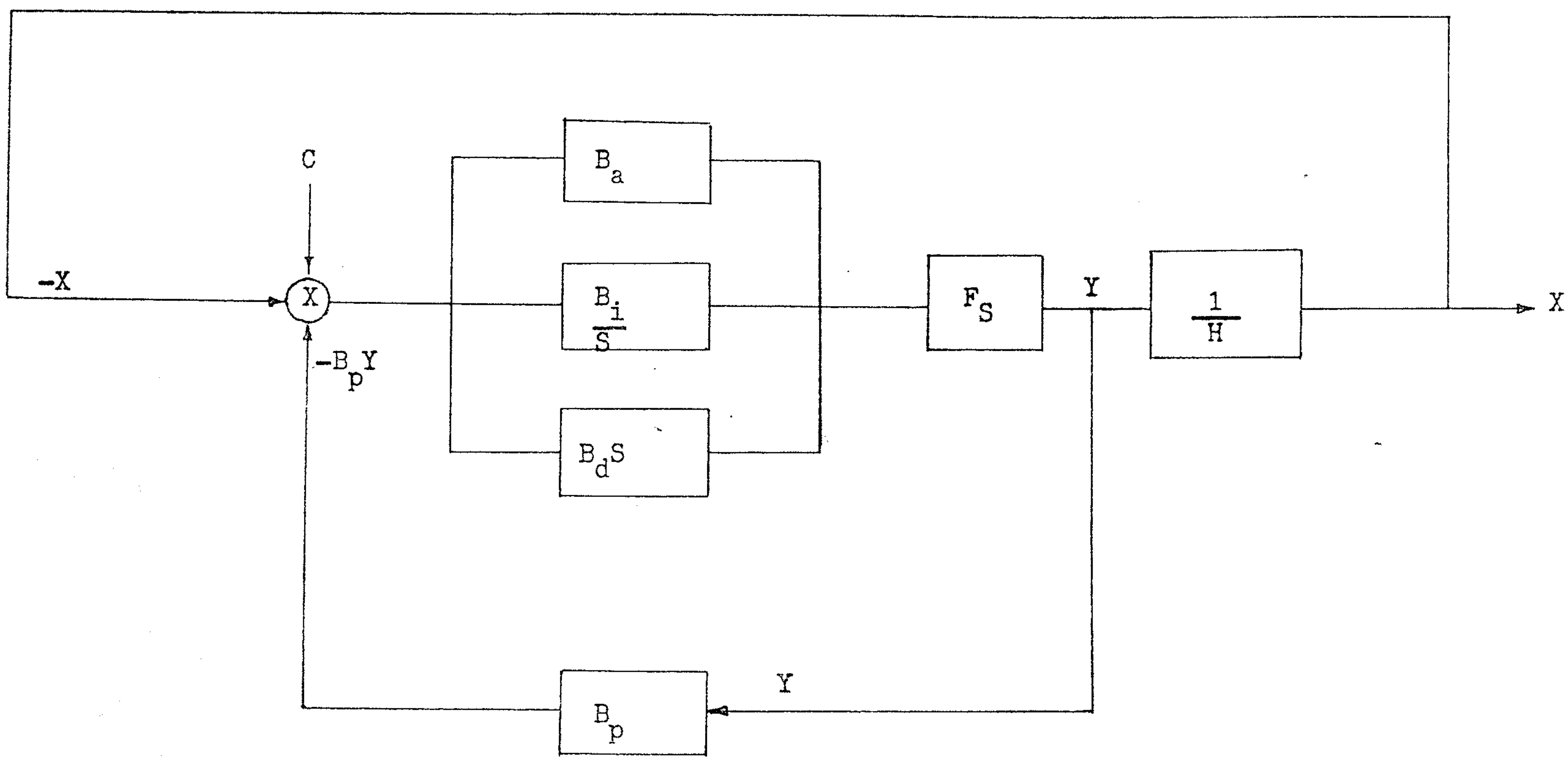
$B_i = K_2 \frac{T_m}{T_w^2}$

Where: K_1, K_2 are constant.

T_m = Mechanical Starting Time

T_w = Water Starting Time

The block diagram representation of the governor equation is given in Figure B 1.



GOVERNOR EQUATION

$$Y = (B_a + \frac{B_i}{S} + B_dS)(C-X-B_pY)\ F_{(s)}$$

FIGURE B 1 BLOCK DIAGRAM REPRESENTATION OF GOVERNOR EQUATION

APPENDIX C

Governor response test results obtained for various gain (B_p, B_t, T_d, T_n) values are given in Figures C 1 (a) to C 1 (h).

Where: B_p = Permanent speed droop
B_t = Temporary speed droop
T_d = Dashpot time constant
T_n = Acceleration time constant

The calibration charts of these parameters and a basic governor signal flow diagram are also included as shown in Figure C 2 and Figure C 3.

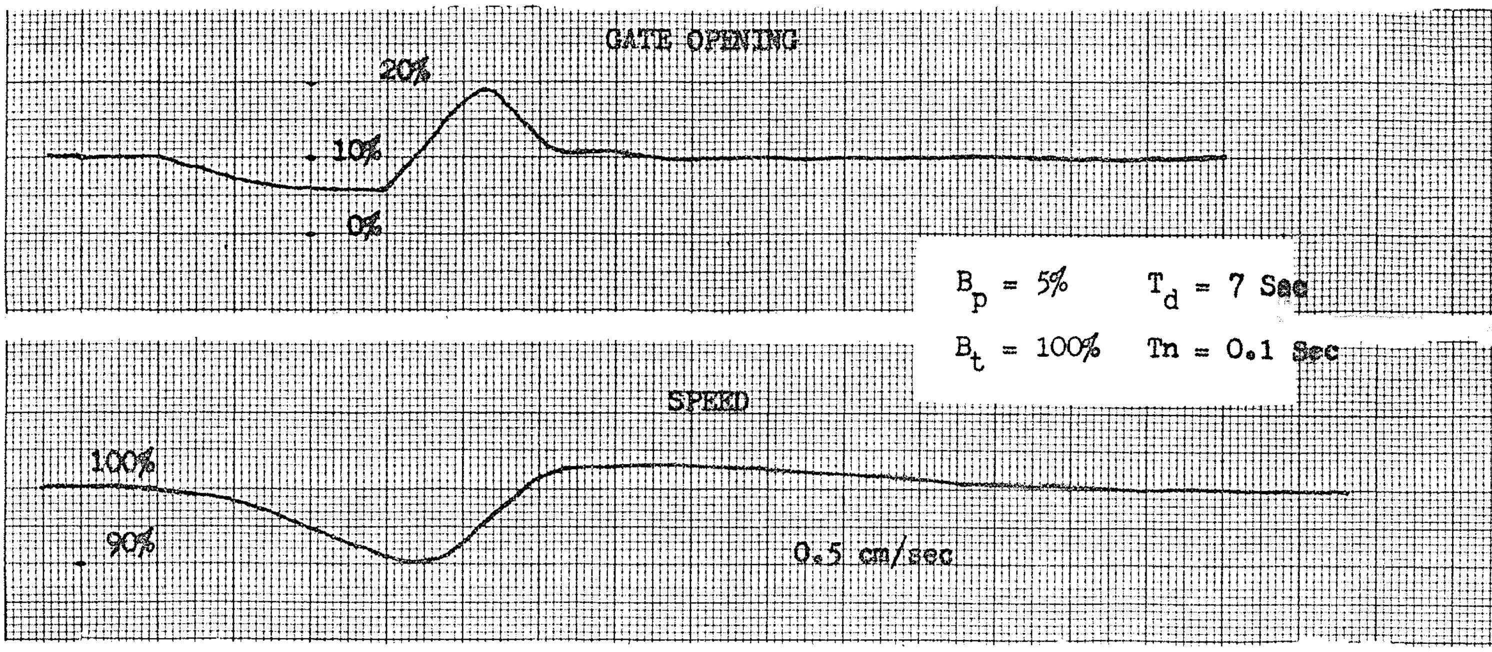


FIGURE C 1 (a)

GATE OPENING AND SPEED TRACES
OBTAINED DURING GOVERNOR RESPONSE TEST

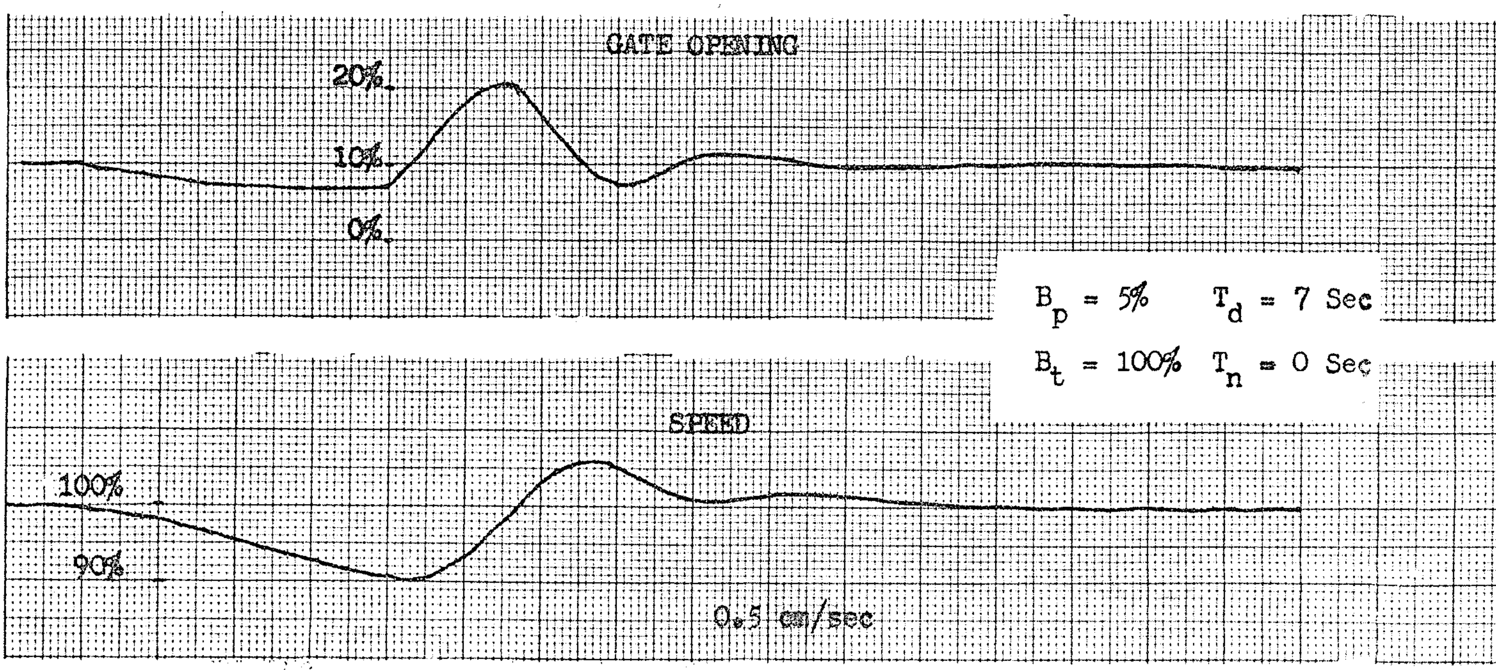


FIGURE C 1 (b)

GATE OPENING AND SPEED TRACES
OBTAINED DURING GOVERNOR RESPONSE TEST

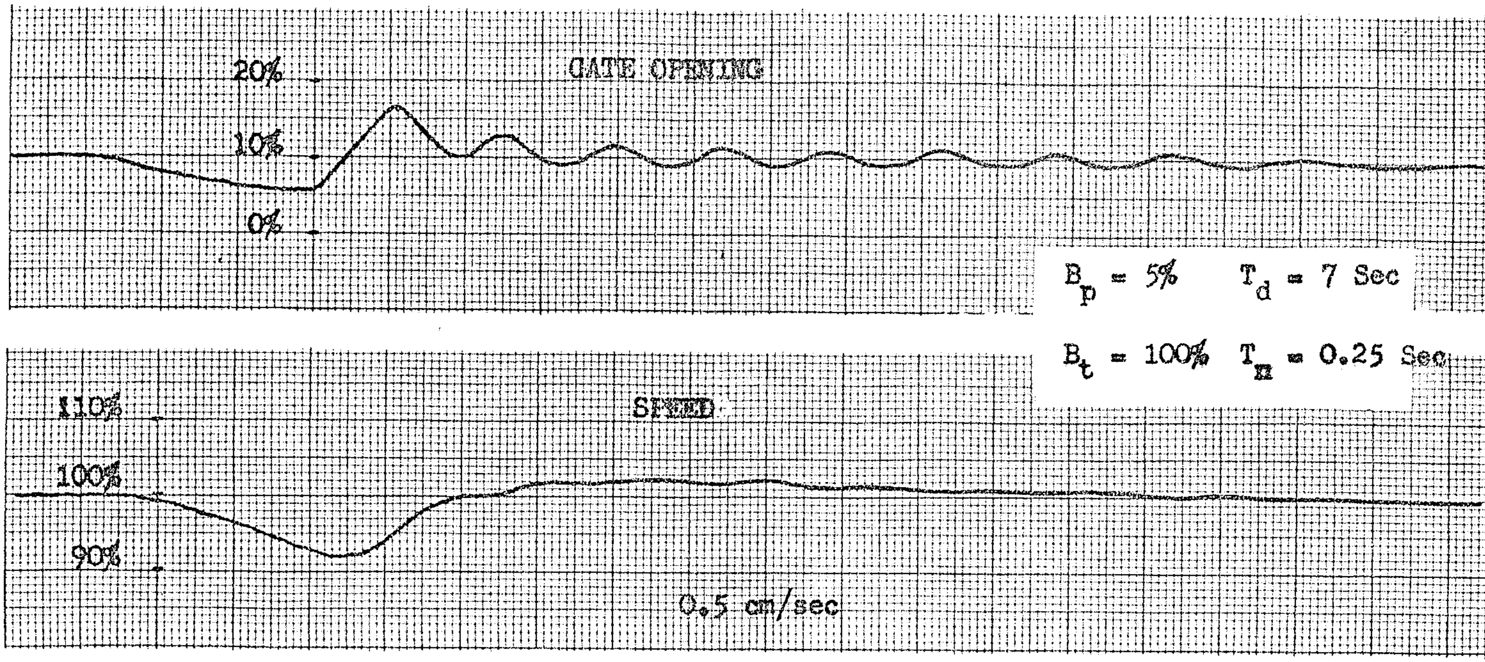


FIGURE C 1 (c)

GATE OPENING AND SPEED TRACES
OBTAINED DURING GOVERNOR RESPONSE TEST

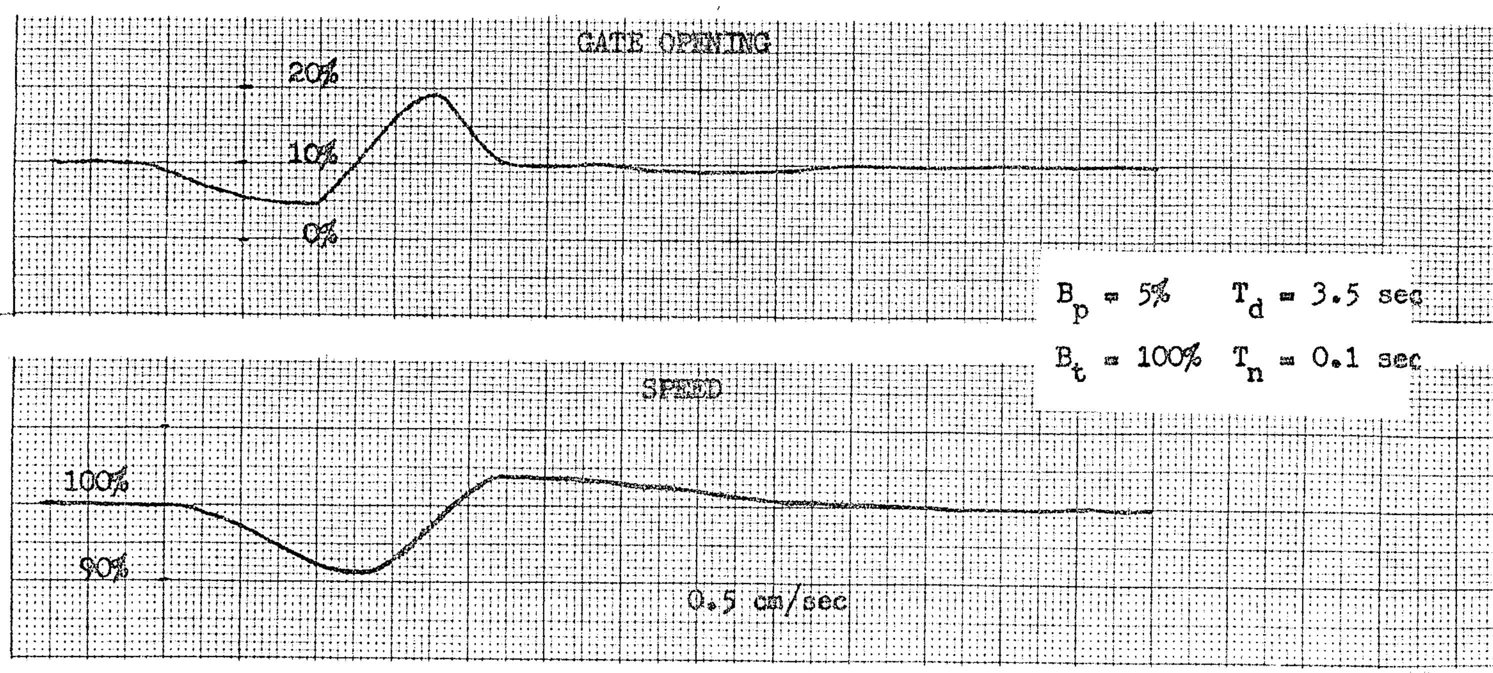


FIGURE C 1 (d)

GATE OPENING AND SPEED TRACES
OBTAINED DURING GOVERNOR RESPONSE TEST

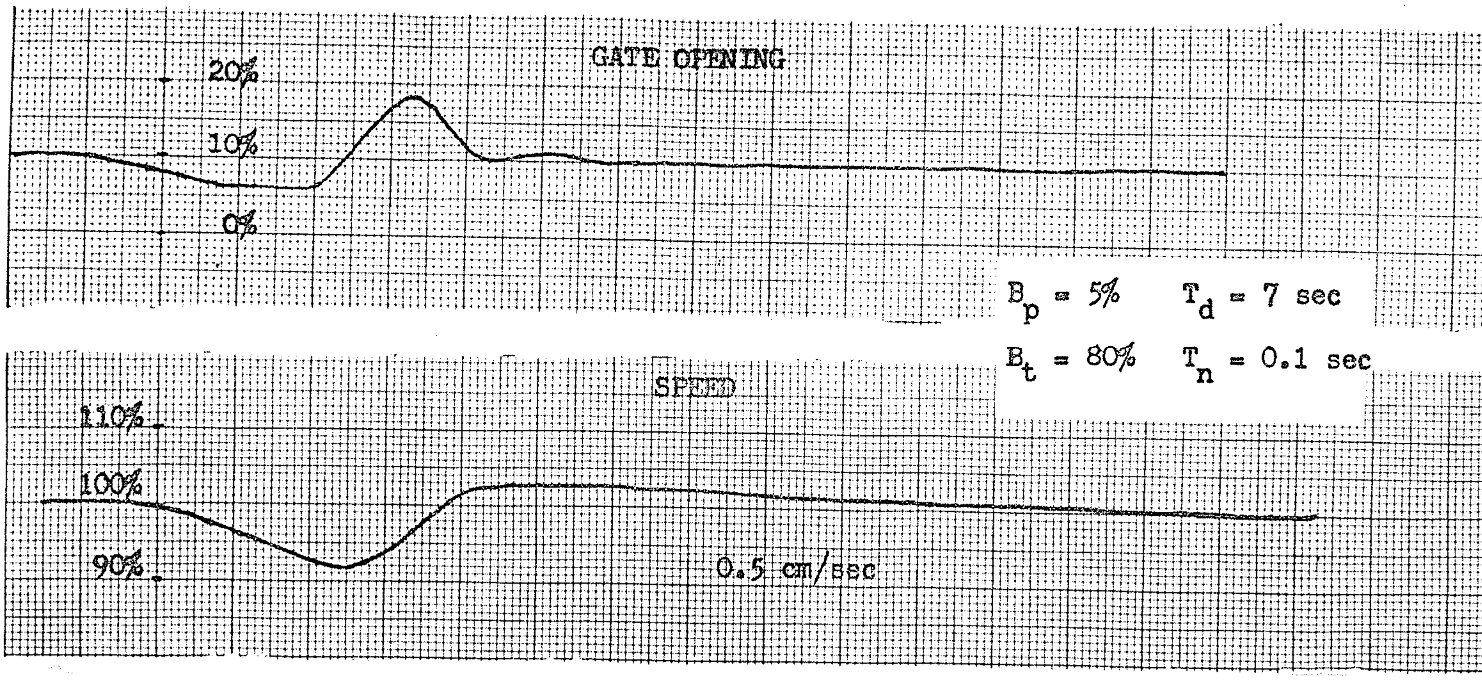


FIGURE C 1 (e)

GATE OPENING AND SPEED TRACES
OBTAINED DURING GOVERNOR RESPONSE TEST

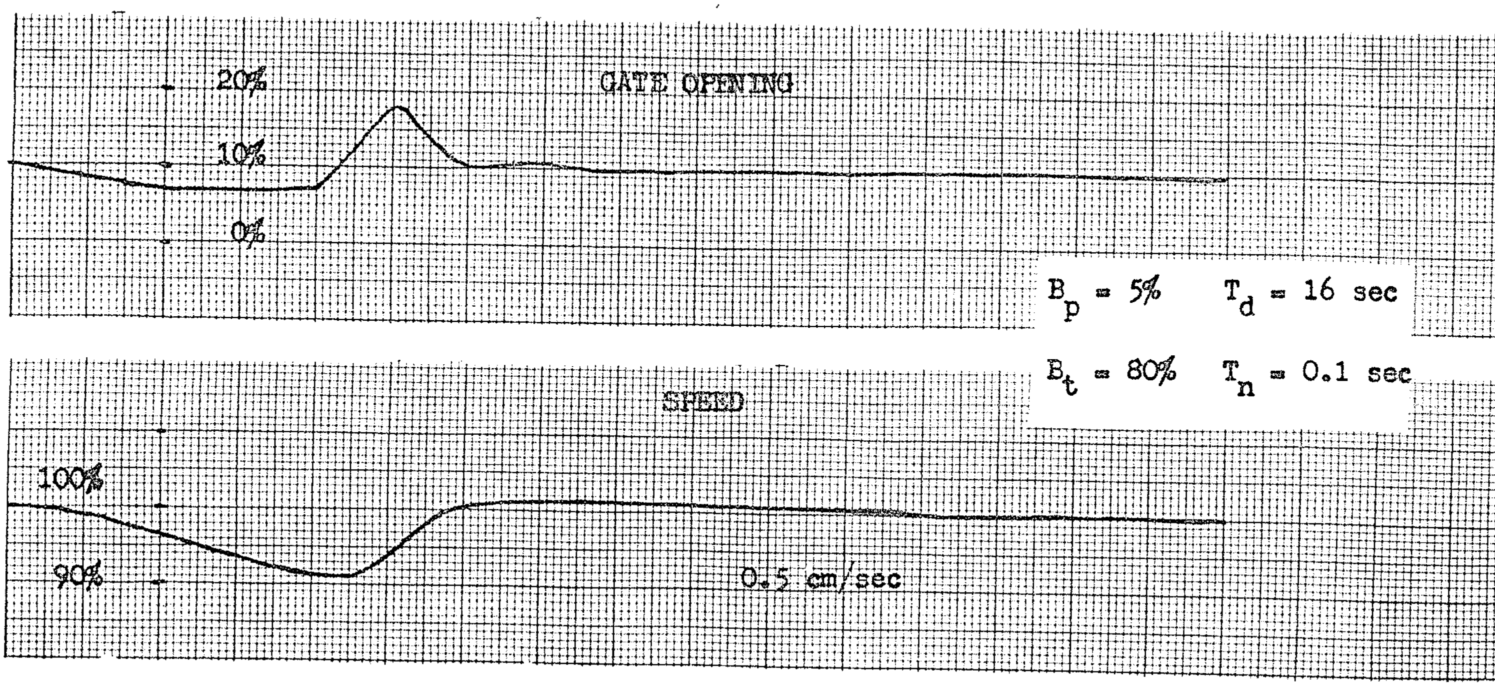


FIGURE C 1 (f)

GATE OPENING AND SPEED TRACES
OBTAINED DURING GOVERNOR RESPONSE TEST

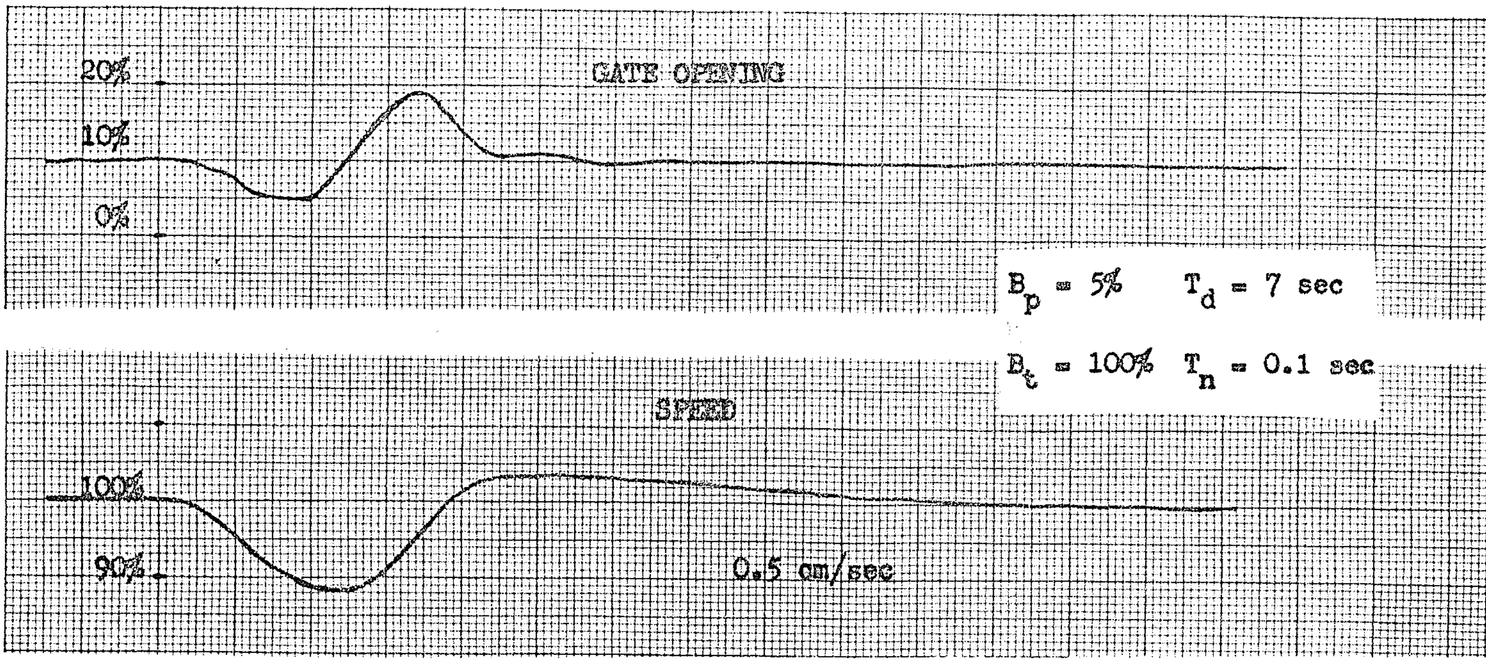


FIGURE C 1 (g)

GATE OPENING AND SPEED TRACES
OBTAINED DURING GOVERNOR RESPONSE TEST

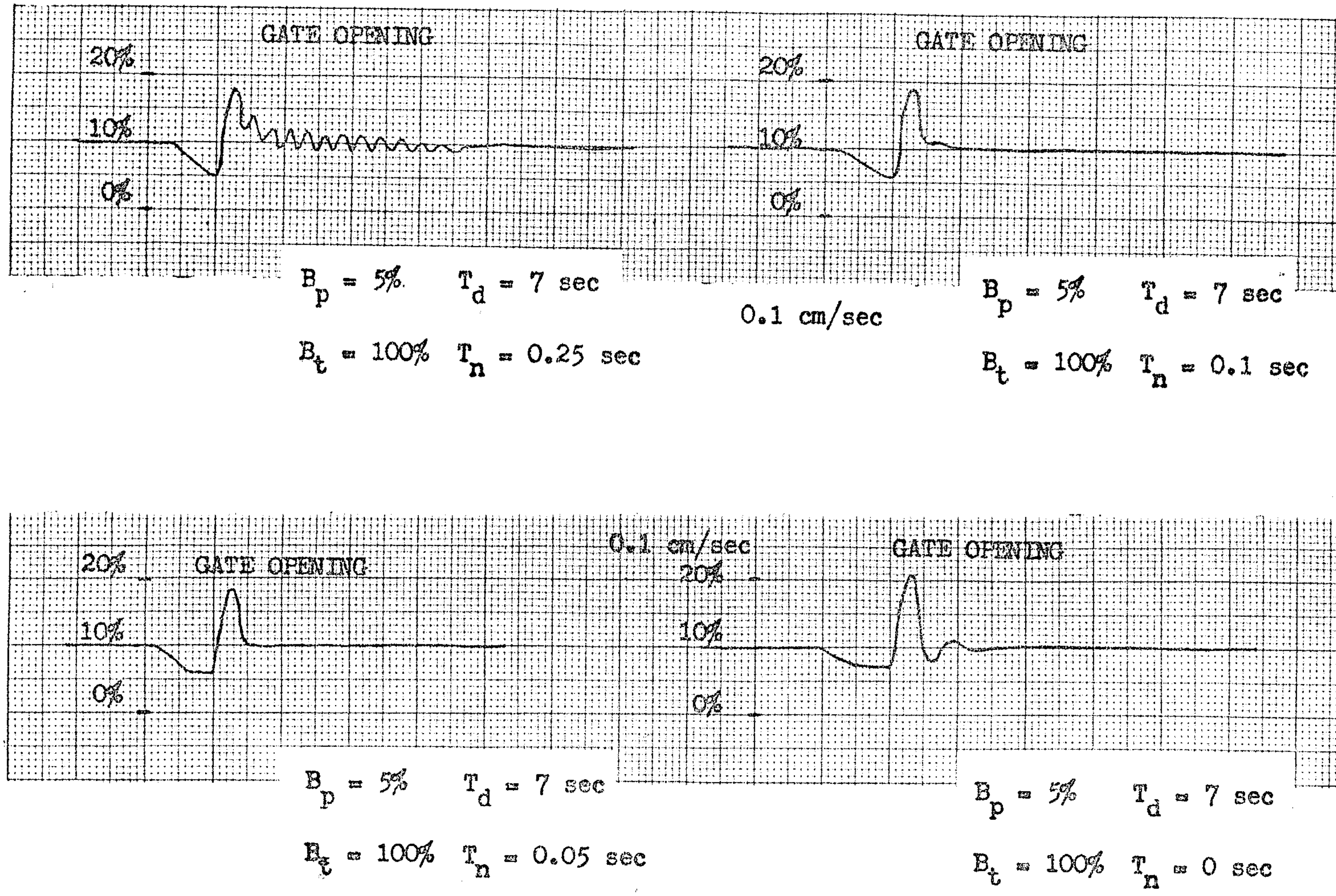


FIGURE C 1 (h)

GATE OPENING ONLY RECORDED
DURING GOVERNOR RESPONSE TEST

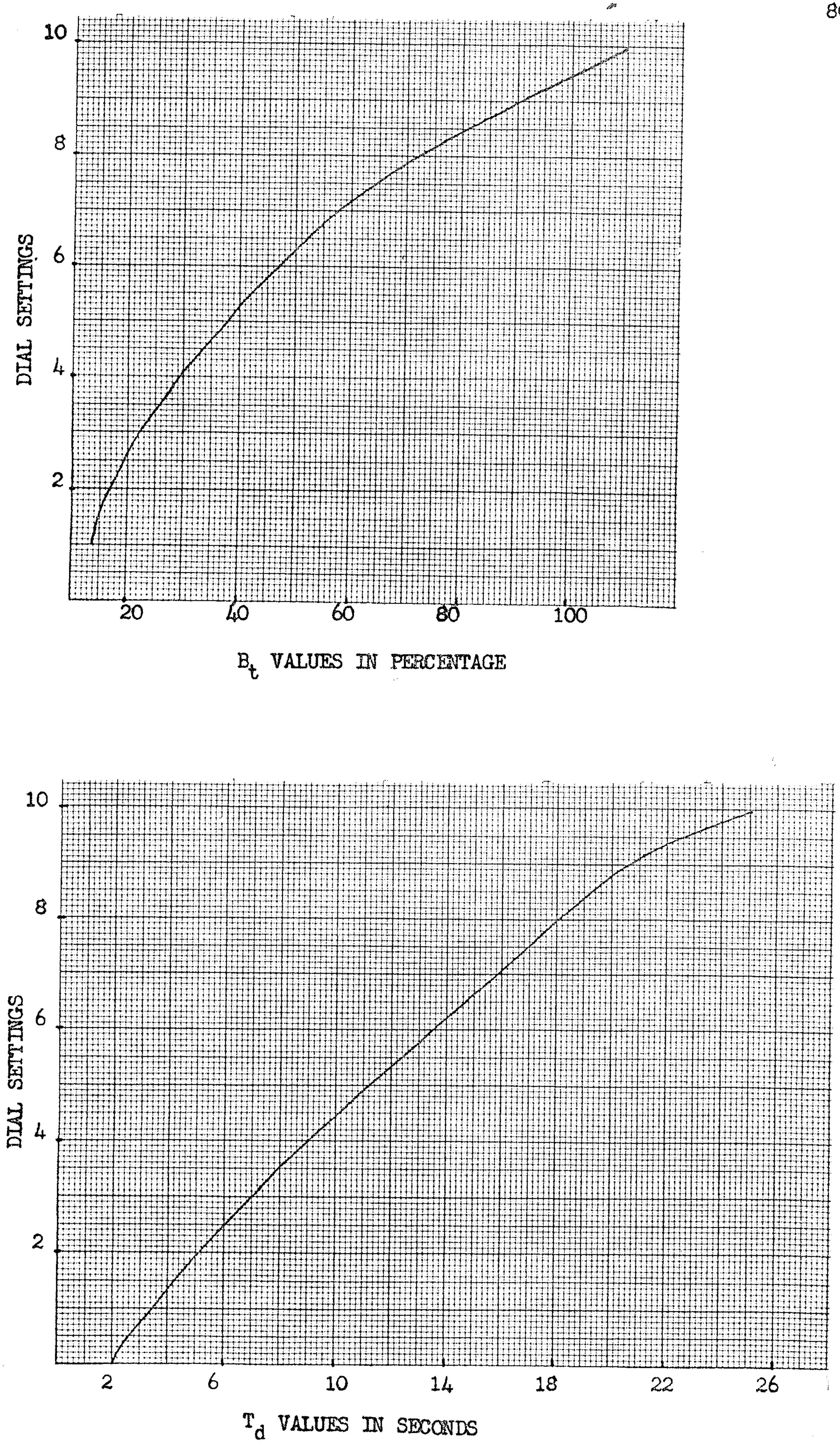


FIGURE C 2 CALIBRATION CHARTS OF B_t , T_d

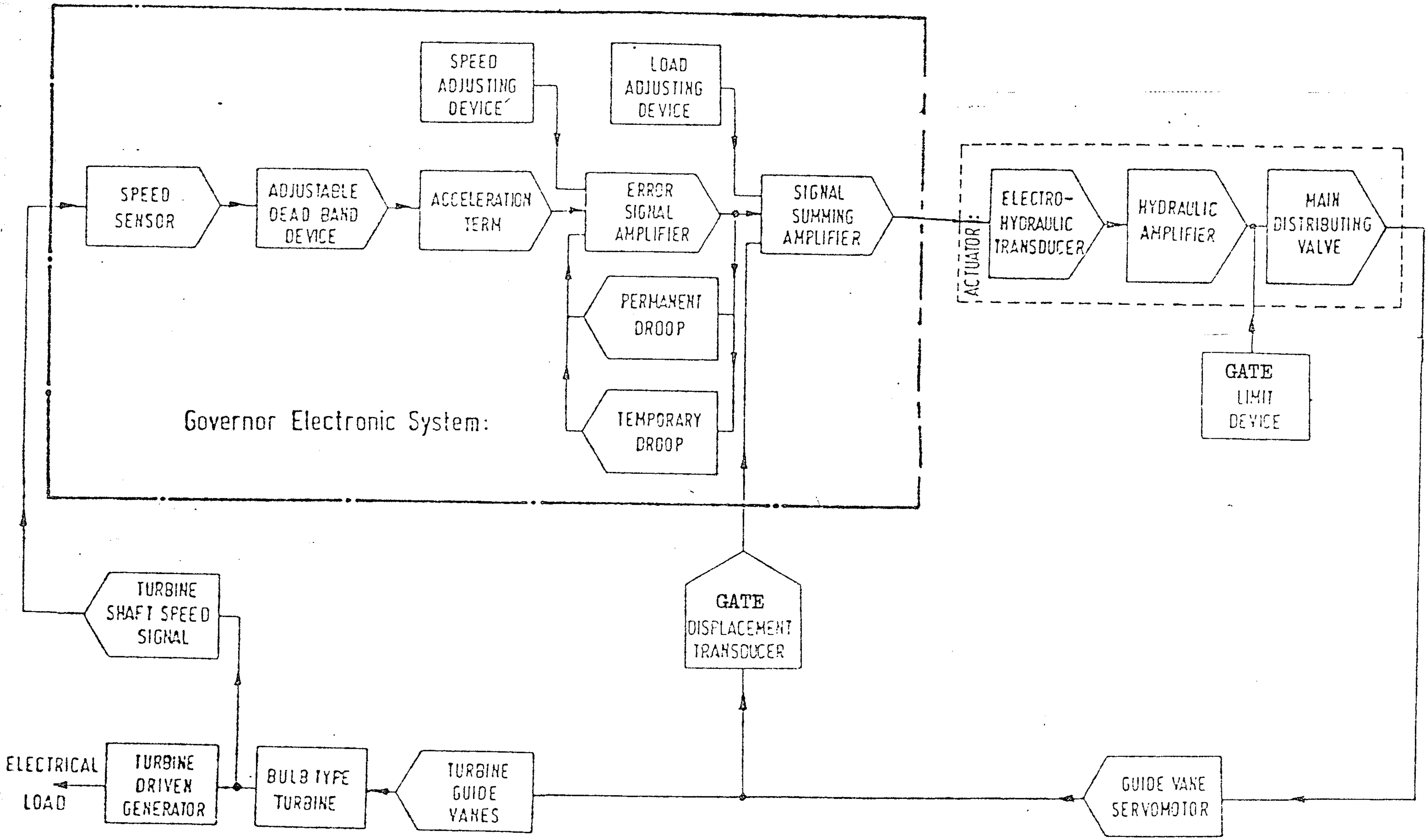


FIGURE C 3

BASIC GOVERNOR SIGNAL FLOW DIAGRAM

APPENDIX D

The load rejection test results under different conditions of governor parameters were obtained.

The gate opening, blade angle and speed traces were recorded during load rejection (Hard Shutdown of 7, 14, 21, 28 and 30.8 MW values) and are reported here.

i) Table D 1 and Figure D 1 (a) cover 7 MW load rejection hard shutdown.
ii) Table D 2 and Figure D 2 (a) to D 2 (e) cover 14 MW load rejection hard shutdown.
iii) Table D 3 and Figure D 3 (a) to D 3 (c) cover 21 MW load rejection hard shutdown.
iv) Table D 4 and Figure D 4 (a) to D 4 (c) cover 28 MW load rejection hard shutdown.
v) Table D 5 and Figure D 5 (a) cover 30.8 MW load rejection hard shutdown.

LOAD REJECTION TESTS

TABLE D 1

TEST NO.	% GATE AT SERVO	BLADE ANGLE AT OIL HEAD	MW BOARD METER	% GATE POSITI-ON SWITCH SETT-ING	SNL LIMIT % GATE	START BLADE ANGLE DEGR-EES	PROG-RAM CLOS-ING % GATE	PROGRAMED CLOSING		HWL FT	TWL FT	GROSS HEAD FT	PERM-ANENT DROOP B_p (POS)	TEMPO-RARY DROOP B_t (POS)	TEMPO-RARY DROOP TIME CONST (POS)	DERIVA-TIVE TIME CONST T_n SEC	MVAR	FIELD VOLTS	FIELD AMPS	STATOR VOLTS	STATOR AMPS	TYPE LOAD REJEC-TION	REMARKS
								ON SPEED %	OFF SPEED %					* **	* **								HARD SHUTDOWN BY
a	34		7	35	25	-9.8°	29.7	120	99	705.28	679.38	25.9	5	9/9	3/3	0.05	3.5	175	1350	4200	1000	Hard	Emergency Valve

* —NO LOAD VALUES
** —ON LINE VALUES
HWL—FOREBAY WATER LEVEL
TWL—TAILRACE WATER LEVEL
SNL—SPEED NO LOAD

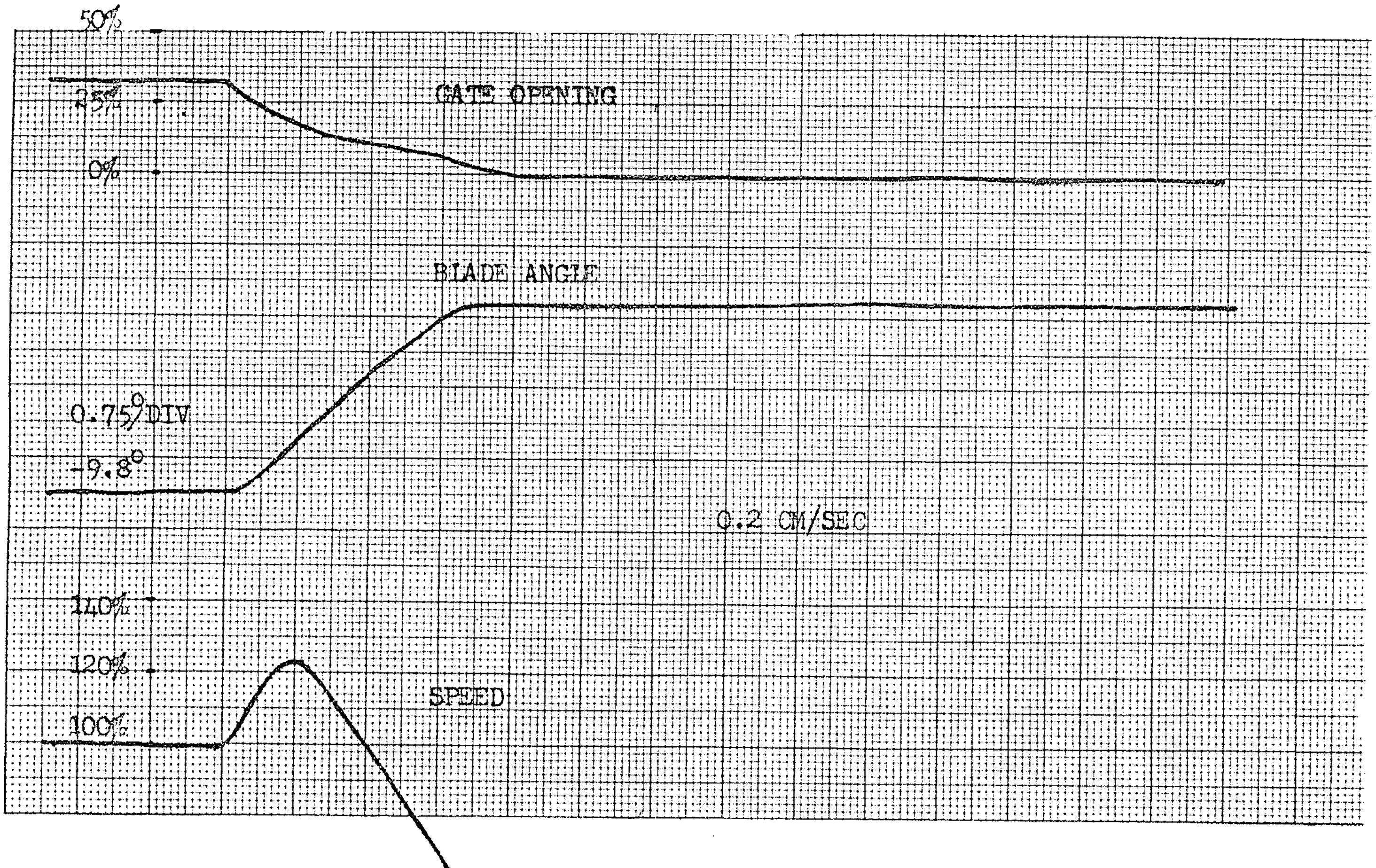


FIGURE D 1 (a)
7 MW LOAD REJECTION HARD SHUTDOWN

LOAD REJECTION TESTS
TABLE D2

TEST NO.	% GATE AT SERVO	BLADE ANGLE AT OIL HEAD	MW BOARD METER	% GATE POSITI-ON SWITCH SETT-ING	SNL LIMIT % GATE	START BLADE ANGLE DEGR-EES	PROG-RAM CLOS-ING % GATE	PROGRAMED CLOSING ON SPEED	PROGRAMED CLOSING OFF SPEED	HWL FT	TWL FT	GROSS HEAD FT	PERM-ANENT DROOP B_p (POS)	TEMPO-RARY DROOP B_t (POS) * **	TEMPO-RARY DROOP TIME CONST (POS) * **	DERIVA-TIVE TIME CONST T_n SEC	MVAR	FIELD VOLTS	FIELD AMPS	STATOR VOLTS	STATOR AMPS	TYPE LOAD REJEC-TION	REMARKS
a	59	+3.2	14	22	20	+10	25	120	98	703.9	679.5	24.4	5	9/9	3/3	0.05	3	185	1500	4200	2000	Hard	EMERGENCY VALVE
b	55	+1.5	14	22	20	+10	25	120	98	705.38	679.10	26.28	5	9/9	3/3	0.05	3	180	1500	4250	1950	Hard	EMERGENCY VALVE
c	52	+0.6	14	35	23.5	+10.2	29.7	120	99	706.34	680.06	26.28	5	9/9	3/3	0.05	2.5	175	1450	4200	2000	Hard	EMERGENCY VALVE
d	35	-5.5	14	35	11	-10	29.7	120	99	713.44	676.3	37.14	5	9/9	3/3	0.05	3.0	180	1500	4200	2000	Hard	EMERGENCY VALVE
e	54.5	+1.5	14	35	23.5	+10.3	29.7	120	99	705.55	679.72	25.77	5	9/9	3/3	0.05	4.0	180	1550	4200	2000	Hard	EMERGENCY VALVE

* —NO LOAD VALUES
** —ON LINE VALUES
HWL—FOREBAY WATER LEVEL
TWL—TAILRACE WATER LEVEL
SNL—SPEED NO LOAD

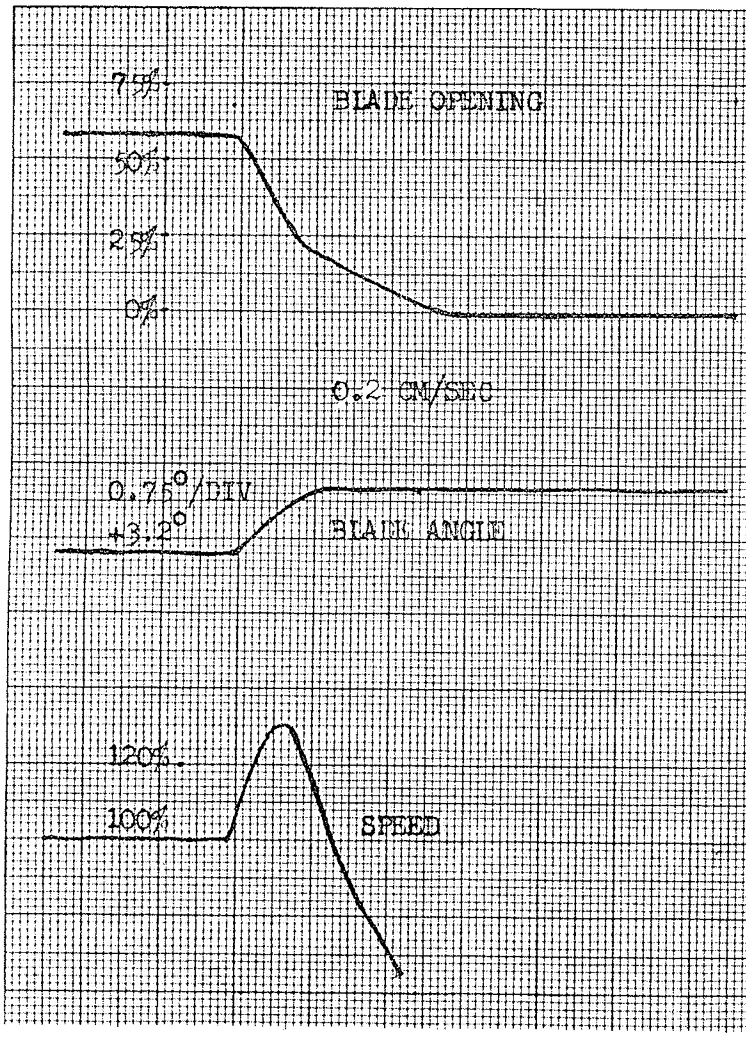


FIGURE D 2 (a)
14 MW LOAD REJECTION HARD SHUTDOWN

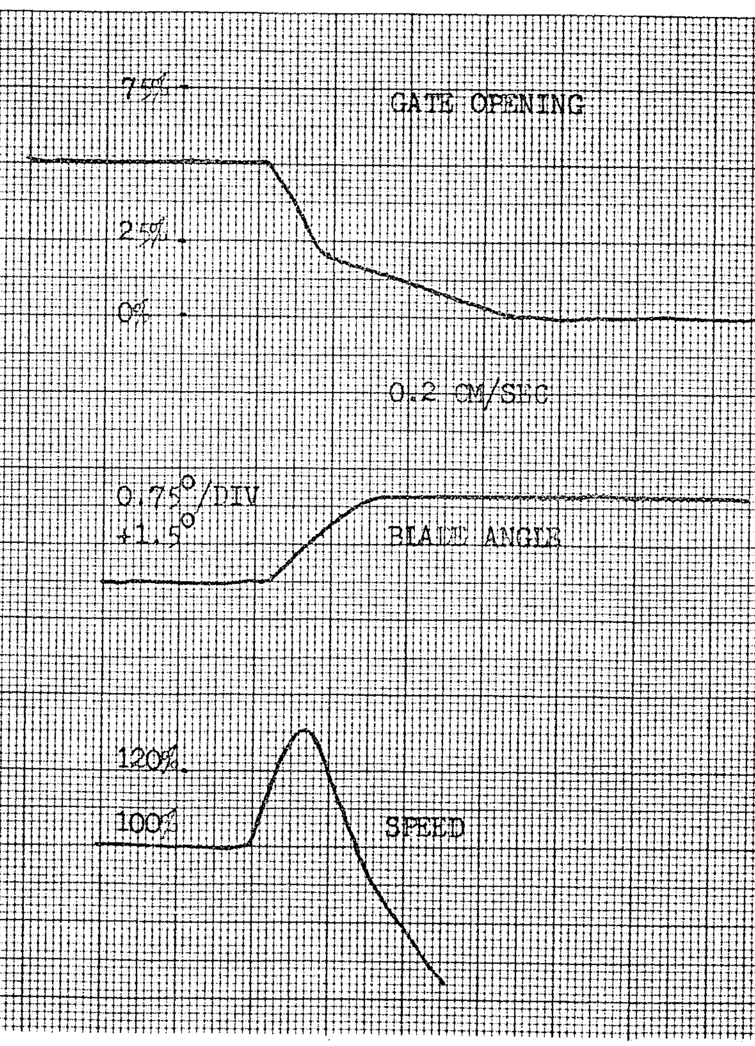
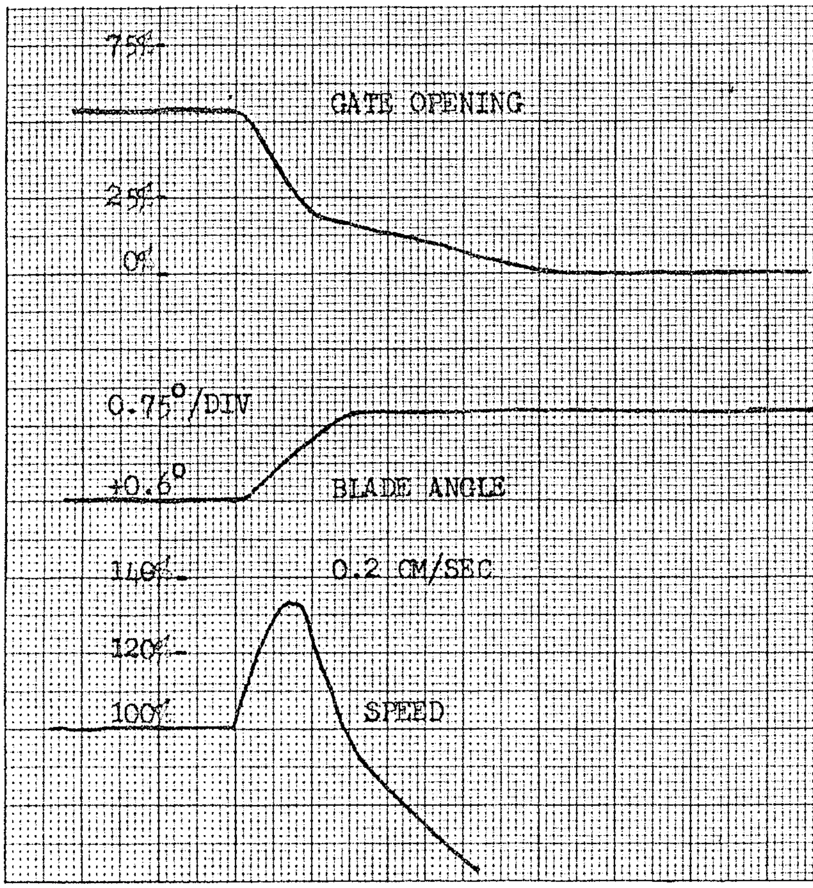


FIGURE D 2 (b)
14 MW LOAD REJECTION HARD SHUTDOWN



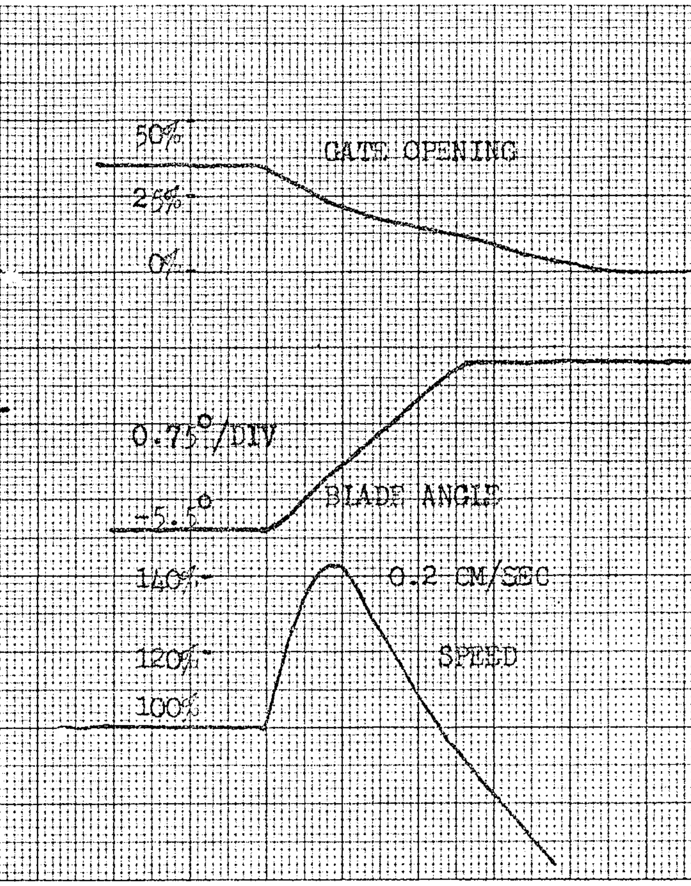


FIGURE D 2 (c)
14 MW LOAD REJECTION HARD SHUTDOWN

FIGURE D 2 (d)
14 MW LOAD REJECTION HARD SHUTDOWN

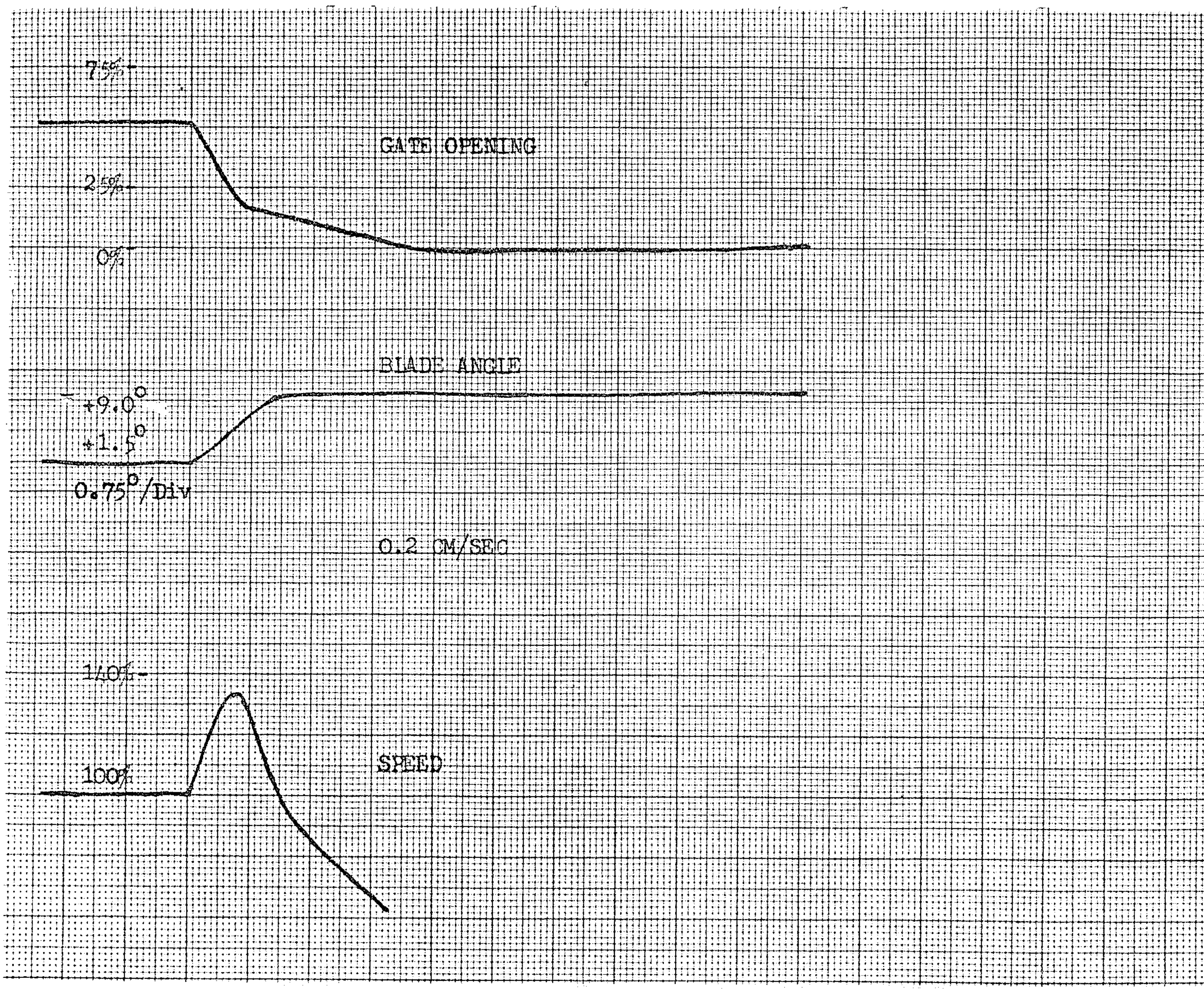


FIGURE D 2 (e)
14 MW LOAD REJECTION HARD SHUTDOWN

LOAD REJECTION TESTS

TABLE D 3

EST NO-	% GATE AT SERVO	BLADE ANGLE AT OIL HEAD	MW BOARD METER	% GATE POSITI--ON SWITCH SETT--ING	SNL LIMIT % GATE	START BLADE ANGLE DEGR--EES	PROG--RAM CLOS--ING % GATE	PROGRAMED CLOSING ON SPEED	PROGRAMED CLOSING OFF SPEED	HWL FT	TWL FT	GROSS HEAD FT	PERM--ANENT DROOP B_p (POS)	TEMPO--RARY DROOP B_t (POS) * **	TEMPO--RARY DROOP TIME CONST (POS) * **	DERIVA--TIVE TIME CONST T_n SEC	MVAR	FIELD VOLTS	FIELD AMPS	STATOR VOLTS	STATOR AMPS	TYPE LOAD REJEC--TION	REMARKS
a	73	+11.2	21	35	23.5	+10.2	29.7	120	99	705.45	679.73	25.72	5	9/9	3/3	0.05	3.0	200	1625	4200	2900	Hard	EMERGENCY VALVE
b	45.5	+2	21	35	11	-10	29.7	120	99	713.48	676.35	37.15	5	9/9	3/3	0.05	4.0	200	1700	4200	2900	Hard	EMERGENCY VALVE
c	69.9	+11.5	21	35	23.5	10.2	29.7	120	99	706.28	680.10	26.18	5	9/9	3/3	0.05	2.5	200	1550	4200	2900	Hard	EMERGENCY VALVE

* — NO LOAD VALUES

** — ON LINE VALUES

HWL — FOREBAY WATER LEVEL

TWL — TAILRACE WATER LEVEL

SNL — SPEED NO LOAD

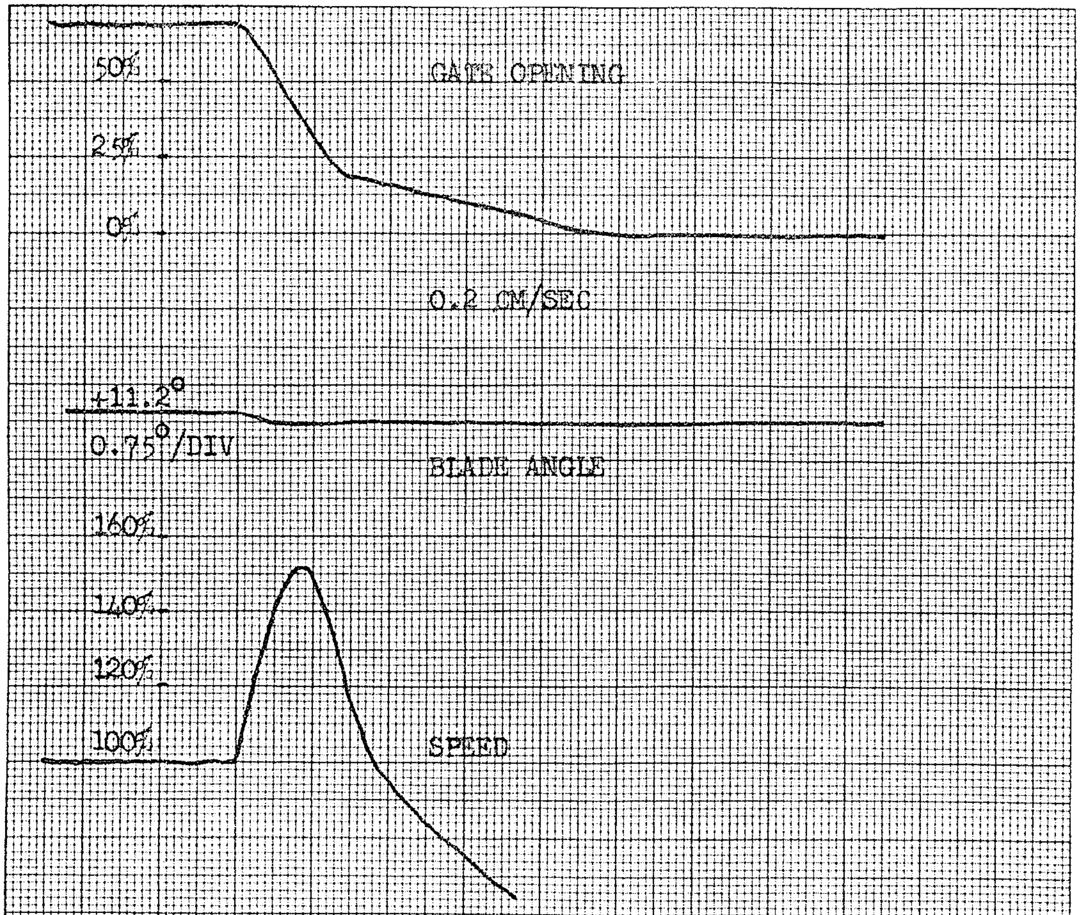


FIGURE D 3 (a)
21 MW LOAD REJECTION HARD SHUTDOWN

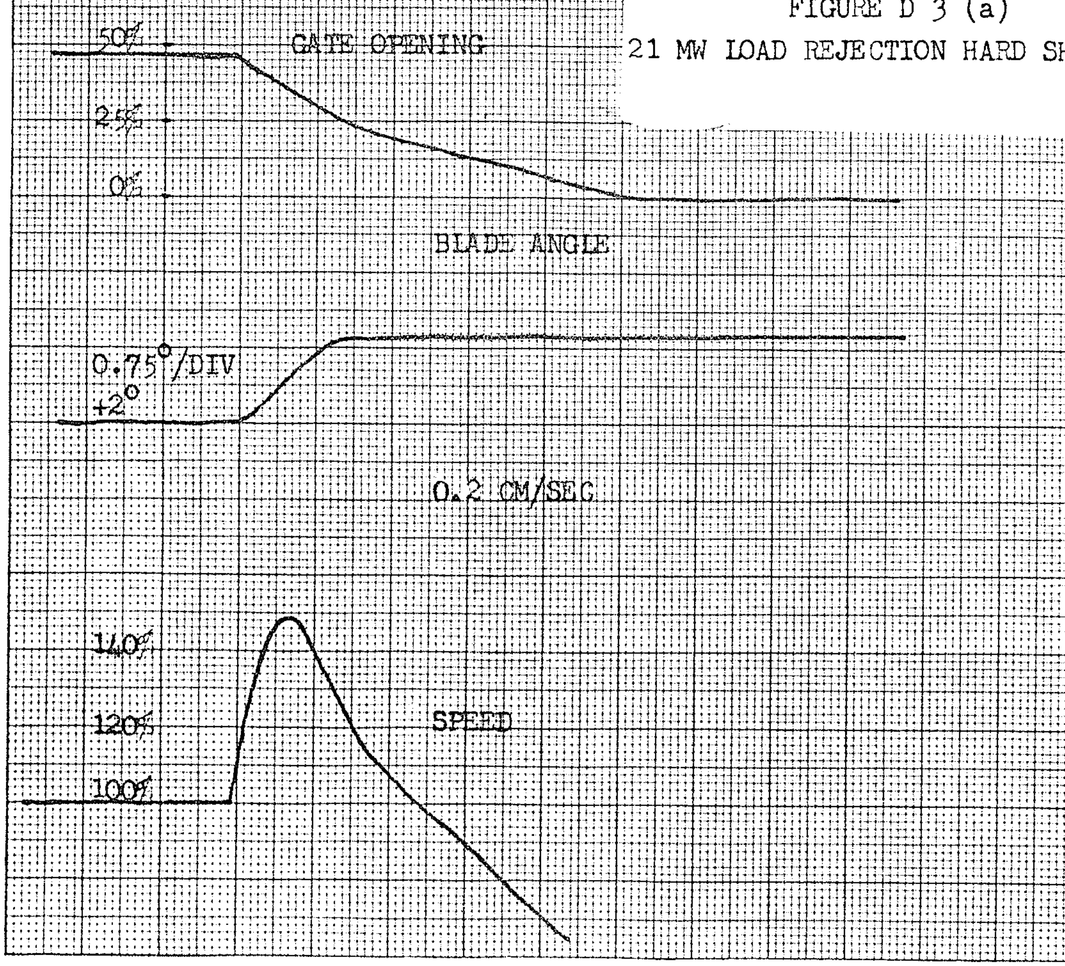


FIGURE D 3 (b)
21 MW LOAD REJECTION HARD SHUTDOWN

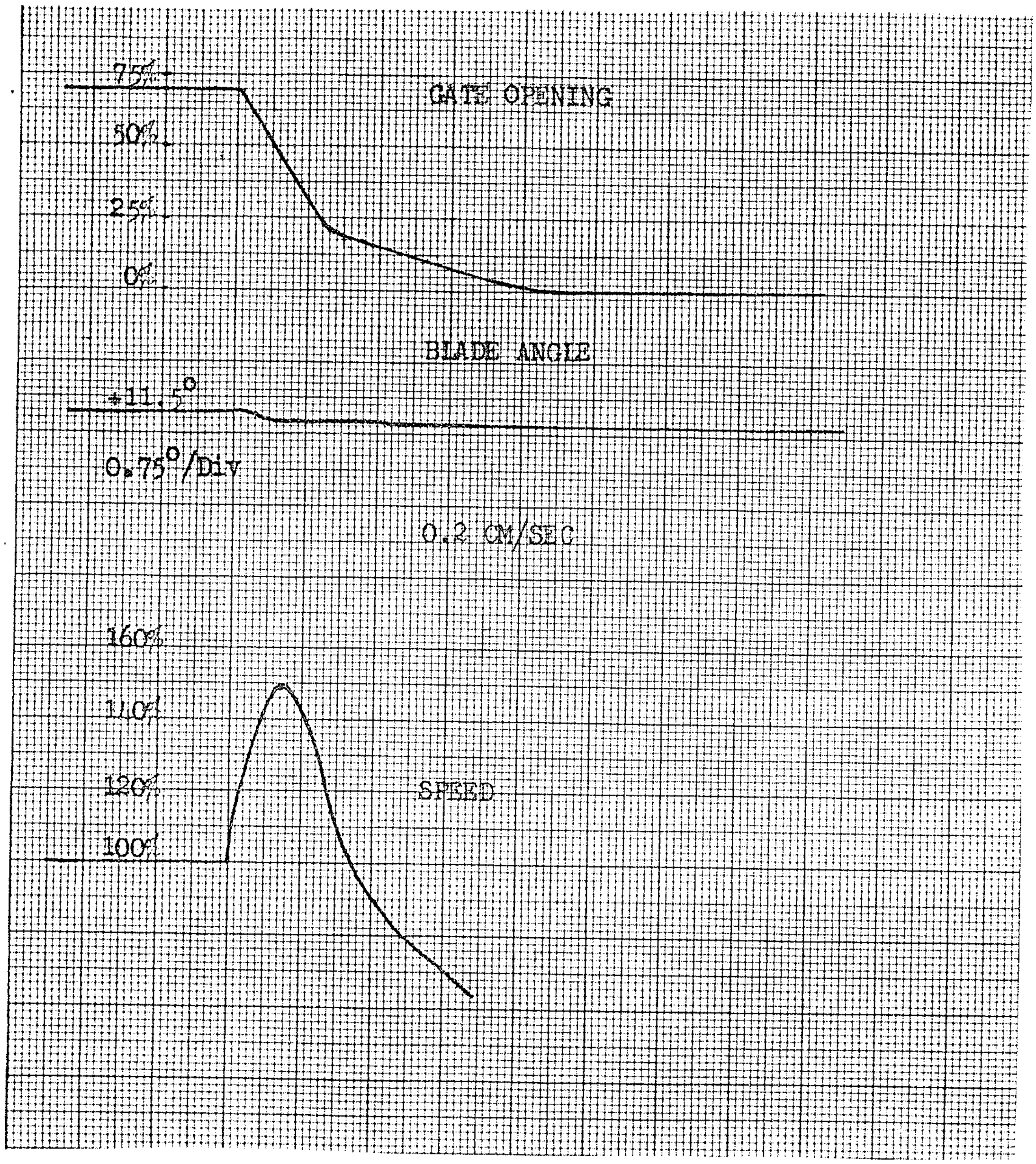


FIGURE D 3 (c)
21 MW LOAD REJECTION HARD SHUTDOWN

LOAD REJECTION TESTS

TABLE D 4

EST NO	% GATE AT SERVO	BLADE ANGLE AT OIL HEAD	MW BOARD METER	% GATE POSITI-ON SWITCH SETT-ING	SNL LIMIT % GATE	START BLADE ANGLE DEGR-EES	PROG-RAM CLOS-ING % GATE	PROGRAMED CLOSING ON SPEED	PROGRAMED CLOSING OFF SPEED	HWL FT	TWL FT	GROSS HEAD FT	PERM-ANENT DROOP B_p (POS)	TEMPO-RARY DROOP B_t (POS) * **	TEMPO-RARY DROOP TIME CONST (POS) * **	DERIVA-TIVE TIME CONST T_n SEC	MVAR	FIELD VOLTS	FIELD AMPS	STATOR VOLTS	STATOR AMPS	TYPE LOAD REJEC-TION	REMARKS
a	92.5	+20°	27.8	35	25	+10.2	29.7	120	99	705.10	679.32	25.78	5	9/9	3/3	0.05	2.5	200	1750	4200	4000	Hard	Emergency Valve
b	95	+20°	28.2	35	23.5	+10.2	29.7	120	99	704.9	679.54	25.36	5	9/9	3/3	0.05	3	220	1750	4200	4000	Hard	Emergency Valve
c	56.5	+ 9.2	28.0	35	11	-10	29.7	120	99	713.36	676.63	36.73	5	9/9	3/3	0.05	5	225	1900	4200	4000	Hard	Emergency Valve

* —NO LOAD VALUES
** —ON LINE VALUES
HWL—FOREBAY WATER LEVEL
TWL—TAILRACE WATER LEVEL
SNL—SPEED NO LOAD

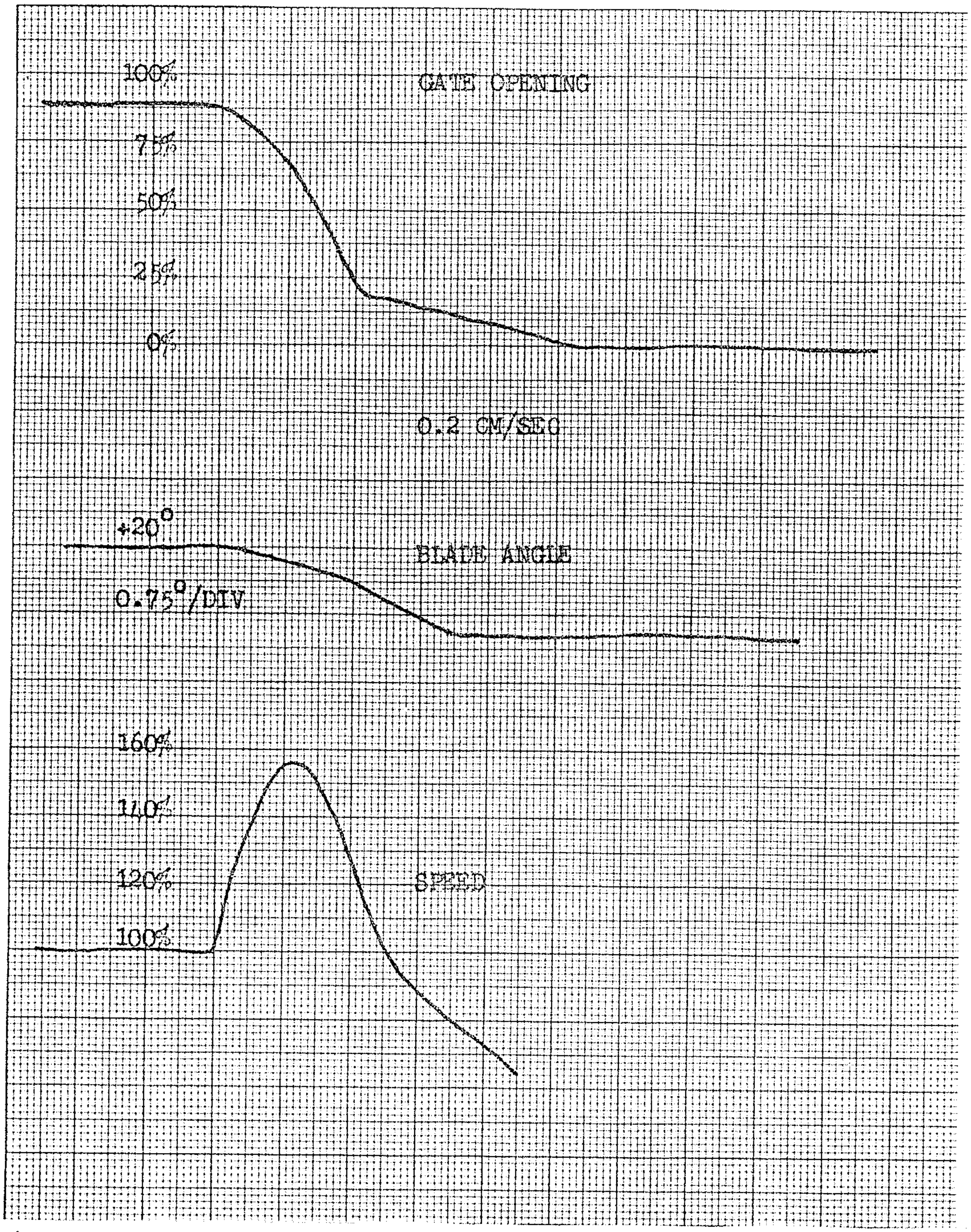


FIGURE D 4 (a)
28 MW LOAD REJECTION HARD SHUTDOWN

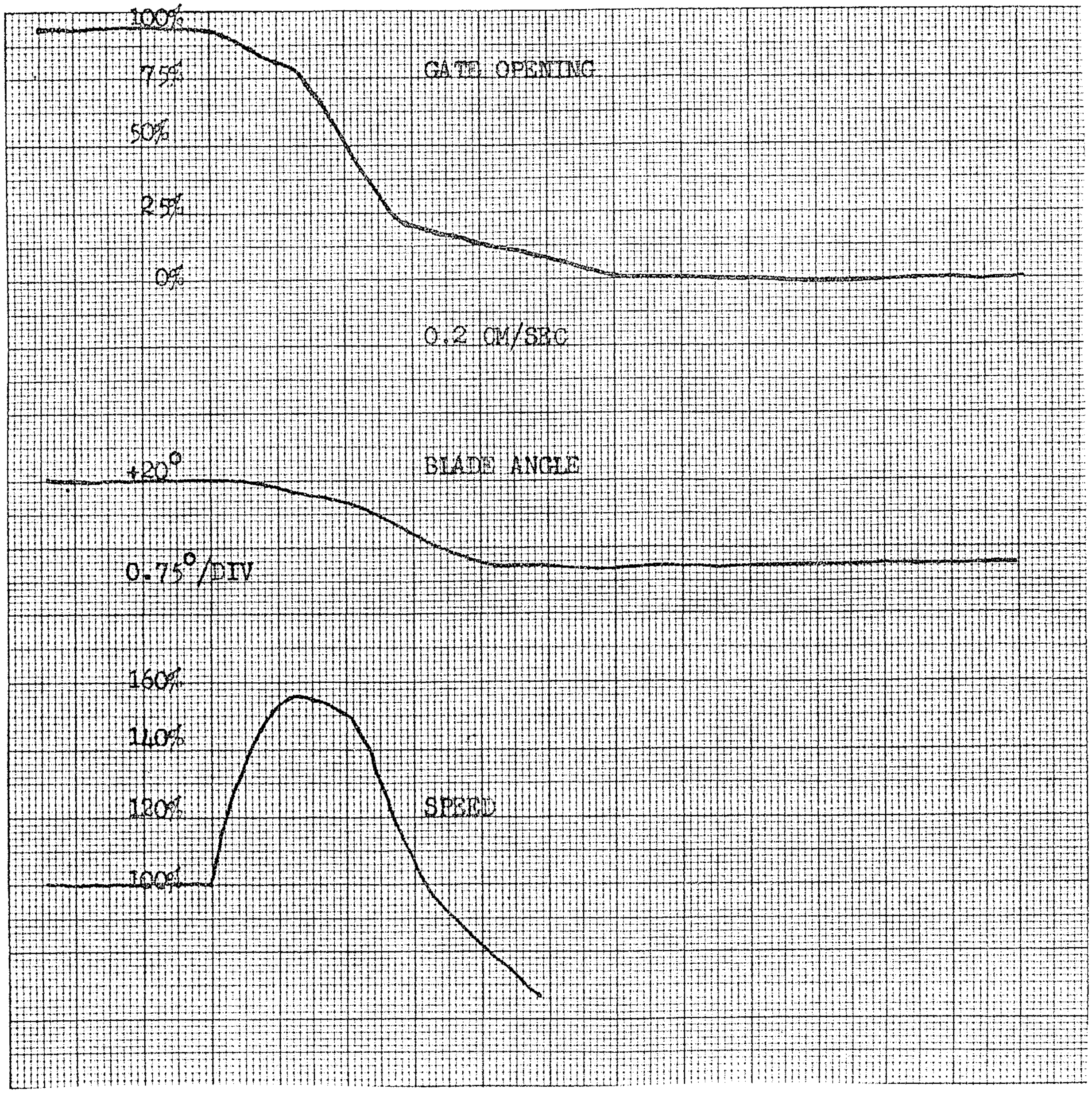


FIGURE D 4 (b)
28 MW LOAD REJECTION HARD SHUTDOWN

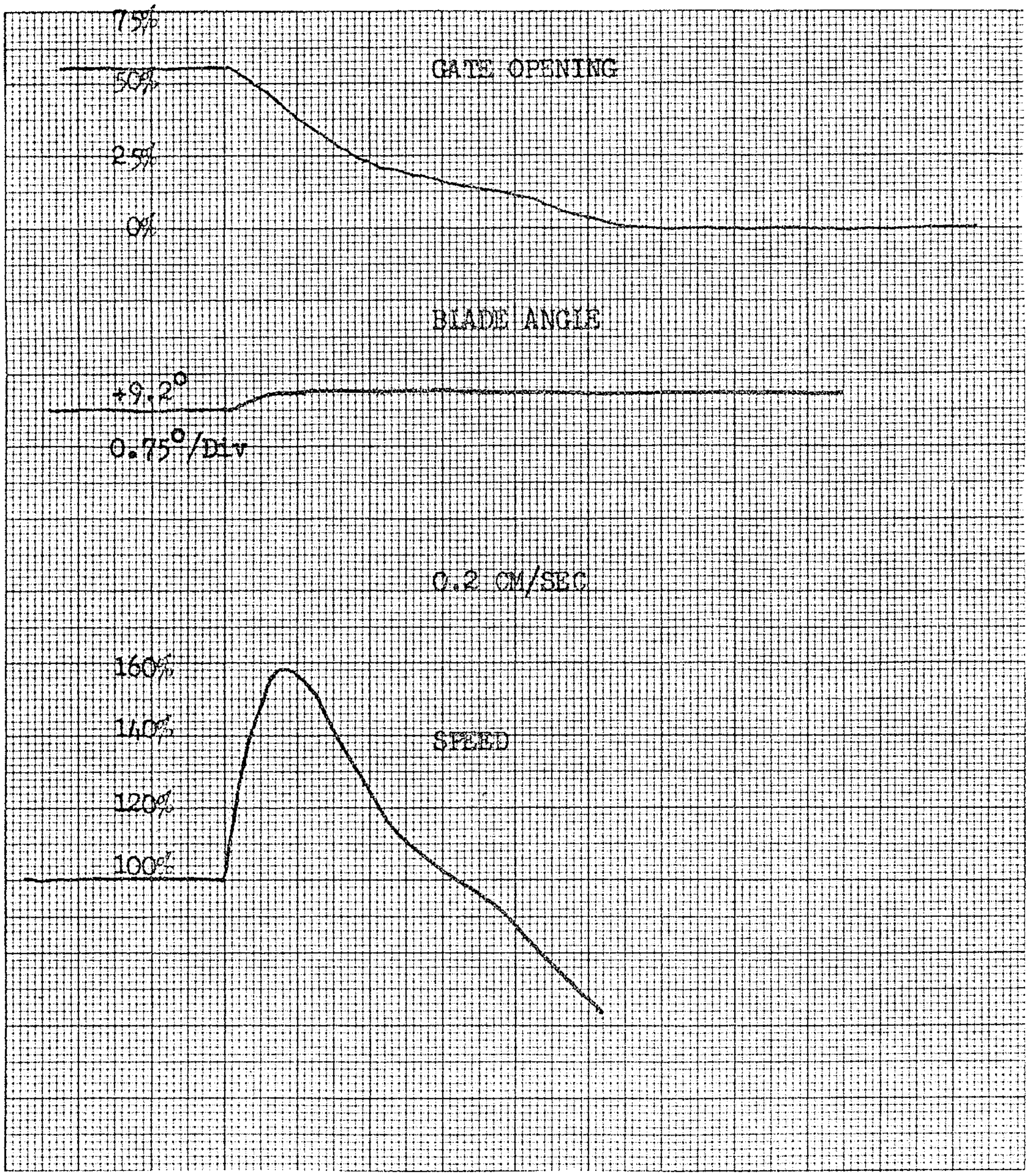


FIGURE D 4 (c)
28 MW LOAD REJECTION HARD SHUTDOWN

LOAD REJECTION TESTS

TABLE D 5

TEST NO.	% GATE AT SERVO	BLADE ANGLE AT OIL HEAD	MW BOARD METER	% GATE POSITI-ON SWITCH SETT-ING	SNL LIMIT % GATE	START BLADE ANGLE DEGR-EES	PROG-RAM CLOS-ING % GATE	PROGRAMED CLOSING ON SPEED	PROGRAMED CLOSING OFF SPEED	HWL FT	TWL FT	GROSS HEAD FT	PERM-ANENT DROOP B_p (POS)	TEMPO-RARY DROOP B_t (POS) * **	TEMPO-RARY DROOP TIME CONST (POS) * **	DERIVA-TIVE TIME CONST T_n SEC	MVAR	FIELD VOLTS	FIELD AMPS	STATOR VOLTS	STATOR AMPS	TYPE LOAD REJEC-TION	REMARKS
a	60.5	+12.5	30.8	35	11	-10	29.7	120	99	713.3	676.5	36.8	5	9/9	3/3	0.05	4	225	1900	4160	4300	Hard	Emergency Valve

* —NO LOAD VALUES
** —ON LINE VALUES
HWL—FOREBAY WATER LEVEL
TWL—TAILRACE WATER LEVEL
SNL—SPEED NO LOAD

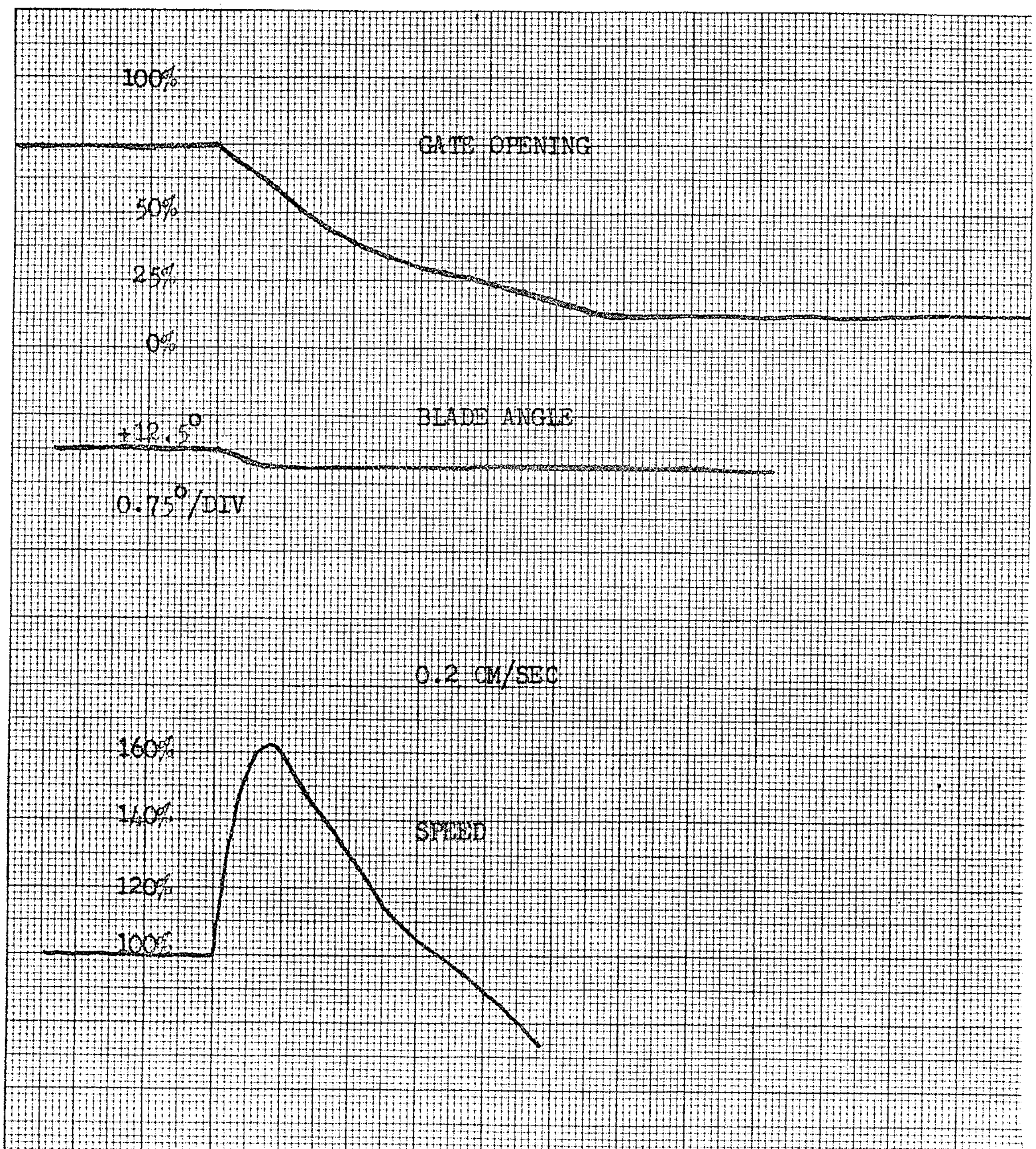


FIGURE D 5 (a)
30.8 MW LOAD REJECTION HARD SHUTDOWN

APPENDIX E

The load rejection test results under different conditions of governor parameters were obtained.

The gate opening, blade angle and speed traces were recorded during load rejection of 7, 14, 21, 28 and 30.8 MW values and the test results are reported here.

i) Table E 1 and Figures E 1 (a) to E 1 (e) cover 7 MW load rejection soft shutdown.

ii) Table E 2 and Figures E 2 (a) to E 2 (j) cover 14 MW load rejection soft shutdown.

iii) Table E 3 and Figures E 3 (a) to E 3 (e) cover 21 MW load rejection soft shutdown.

iv) Table E 4 and Figures E 4 (a) to E 4 (c) cover 28 MW load rejection soft shutdown.

v) Table E 5 and Figure E 5 (a) covers 30.8 MW load rejection soft shutdown.

vi) Figures E 6 (a) to E 6 (c) cover the comparison of speed, gate opening and blade angle obtained for load rejections of 7, 14, 21 and 28 MW soft shutdown and 28 MW hard shutdown.

LOAD REJECTION TESTS

TABLE E 1

EST NO.	% GATE AT SERVO	BLADE ANGLE AT OIL HEAD	MW BOARD METER	% GATE POSITI-ON SWITCH SETT-ING	SNL LIMIT % GATE	START BLADE ANGLE DEGR-EES	PROG-RAM CLOS-ING % GATE	PROGRAMED CLOSING ON SPEED	PROGRAMED CLOSING OFF SPEED	HWL FT	TWL FT	GROSS HEAD FT	PERM-ANENT DROOP B_p (POS)	TEMPO-RARY DROOP B_t (POS) * **	TEMPO-RARY DROOP TIME CONST (POS) * **	DERIVA-TIVE TIME CONST T_n SEC	MVAR	FIELD VOLTS	FIELD AMPS	STATOR VOLTS	STATOR AMPS	TYPE LOAD REJEC-TION	REMARKS
a	38	-9.6	7	22	18	+ 7	25	128	96	704.0	679.5	24.5	5	9/9	3/3	0.05	3.5	175	1450	4200	1000	Soft	SNL IN Service
b	37.5	-9.6	7	36	17	+ 7	31	120	100	704.4	679.3	25.03	5	9/9	3/3	0.05	3.0	175	1400	4200	1000	Soft	SNL IN Service
c	36	-9.5	7	22	20	+10	25	120	100	704.8	679.1	25.7	5	9/9	3/3	0.05	3.0	180	1500	4300	1000	Soft	SNL IN Service
d	35	-9.5	7	22	20	+10	25	120	98	704.9	679.1	25.8	5	9/9	3/3	0.05	3.0	180	1500	4300	1000	Soft	SNL IN Service
e	35	-9.4	7	22	20	+10	25	120	98	704.9	679.2	25.7	5	9/9	3/3	0.05	3.0	175	1500	4250	1000	Soft	SNL DISCONNECTED

* —NO LOAD VALUES

** —ON LINE VALUES

HWL—FOREBAY WATER LEVEL

TWL— TAILRACE WATER LEVEL

SNL— SPEED NO LOAD

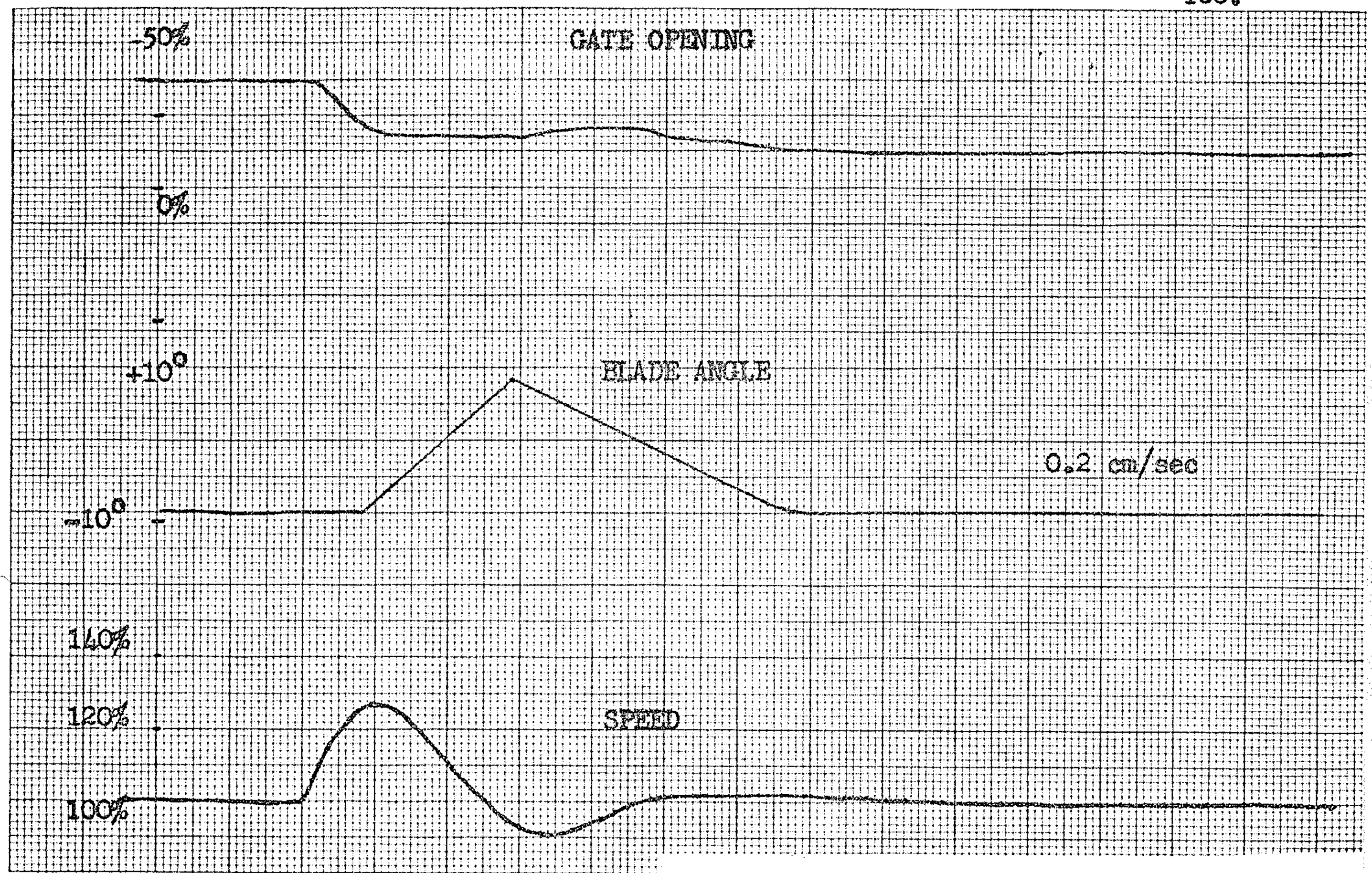


FIGURE E 1 (a)

7 MW LOAD REJECTION SOFT SHUTDOWN

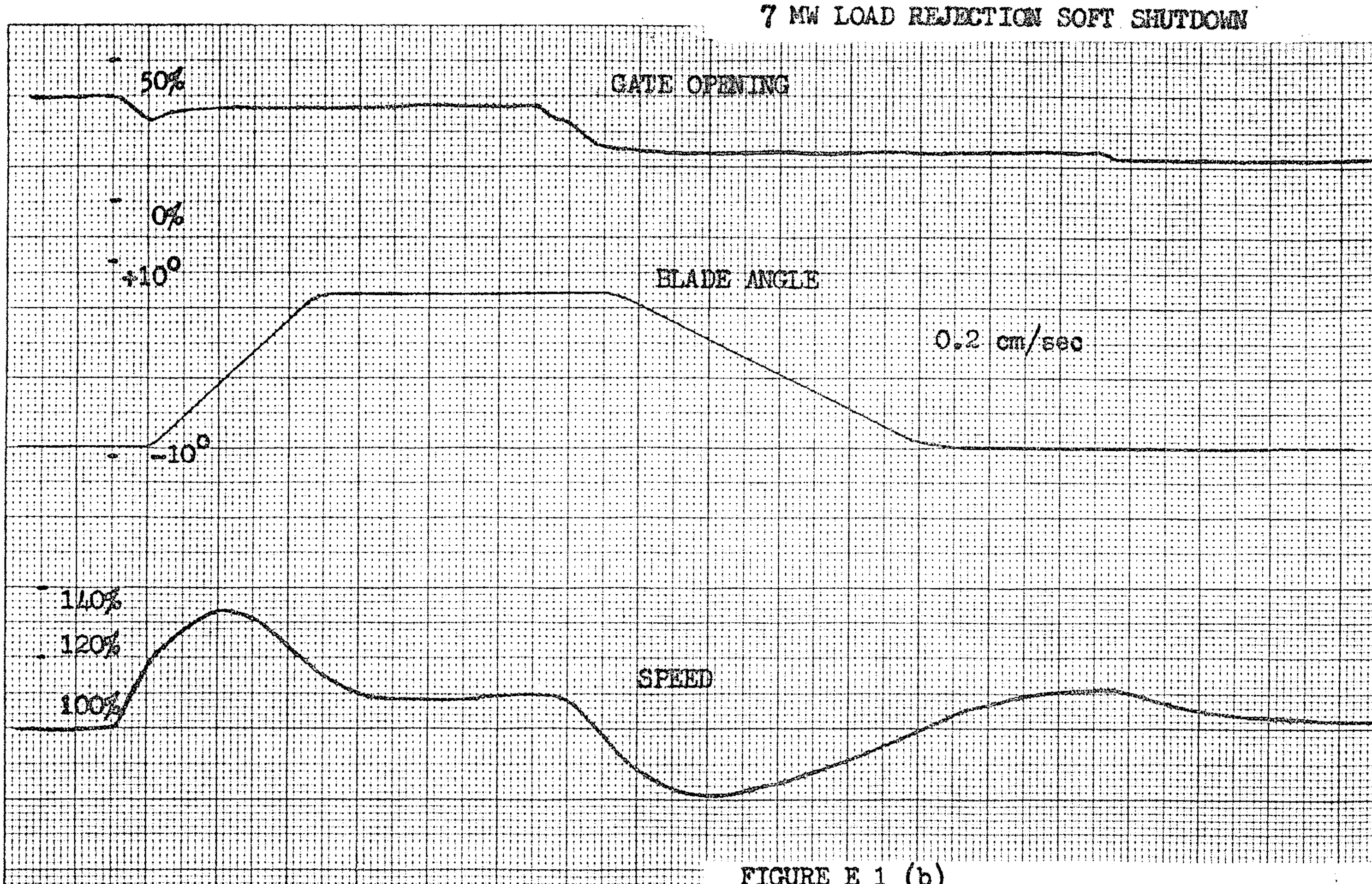


FIGURE E 1 (b)

7 MW LOAD REJECTION SOFT SHUTDOWN

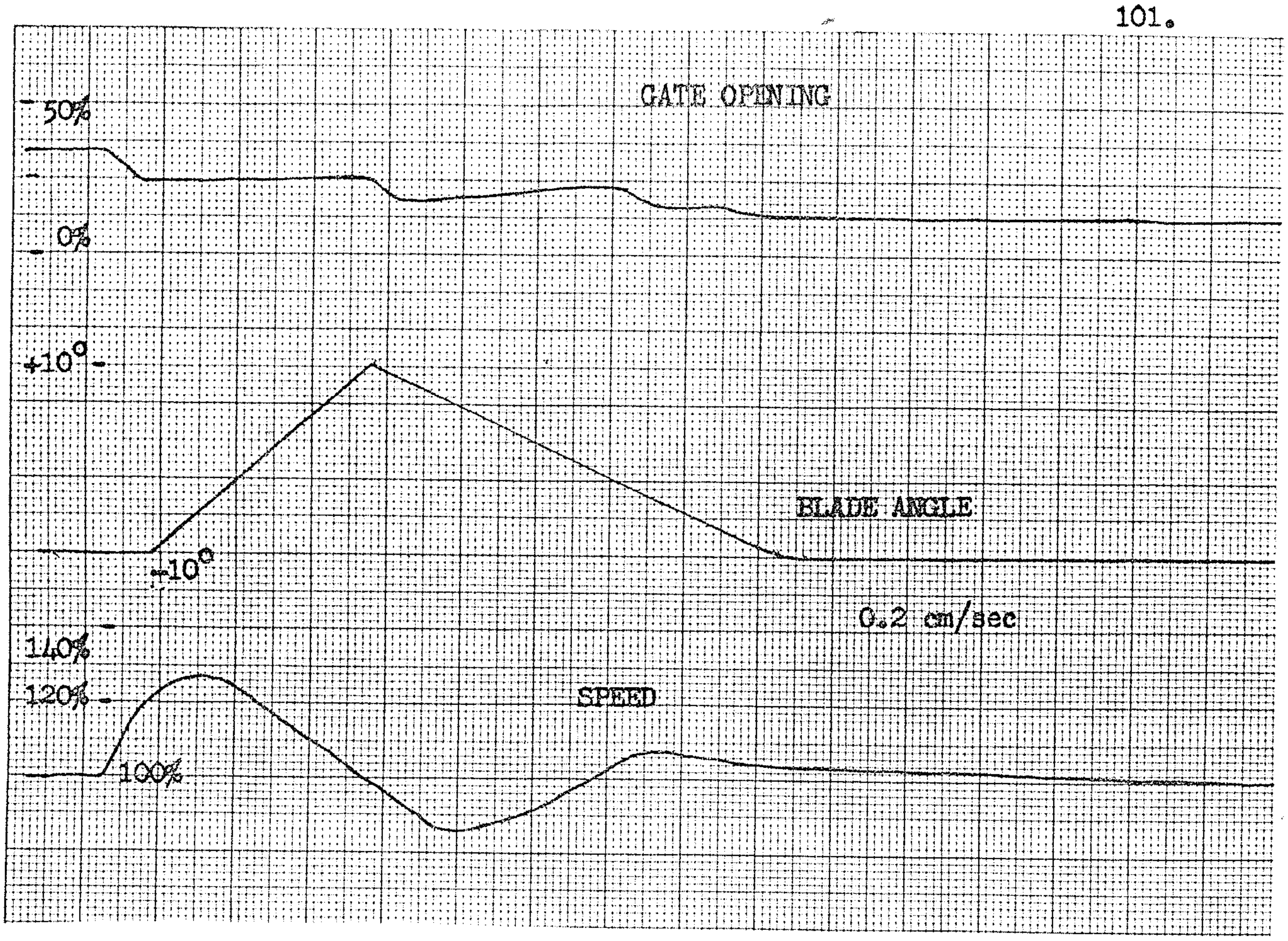


FIGURE E 1 (c) 7 MW LOAD REJECTION SOFT SHUTDOWN

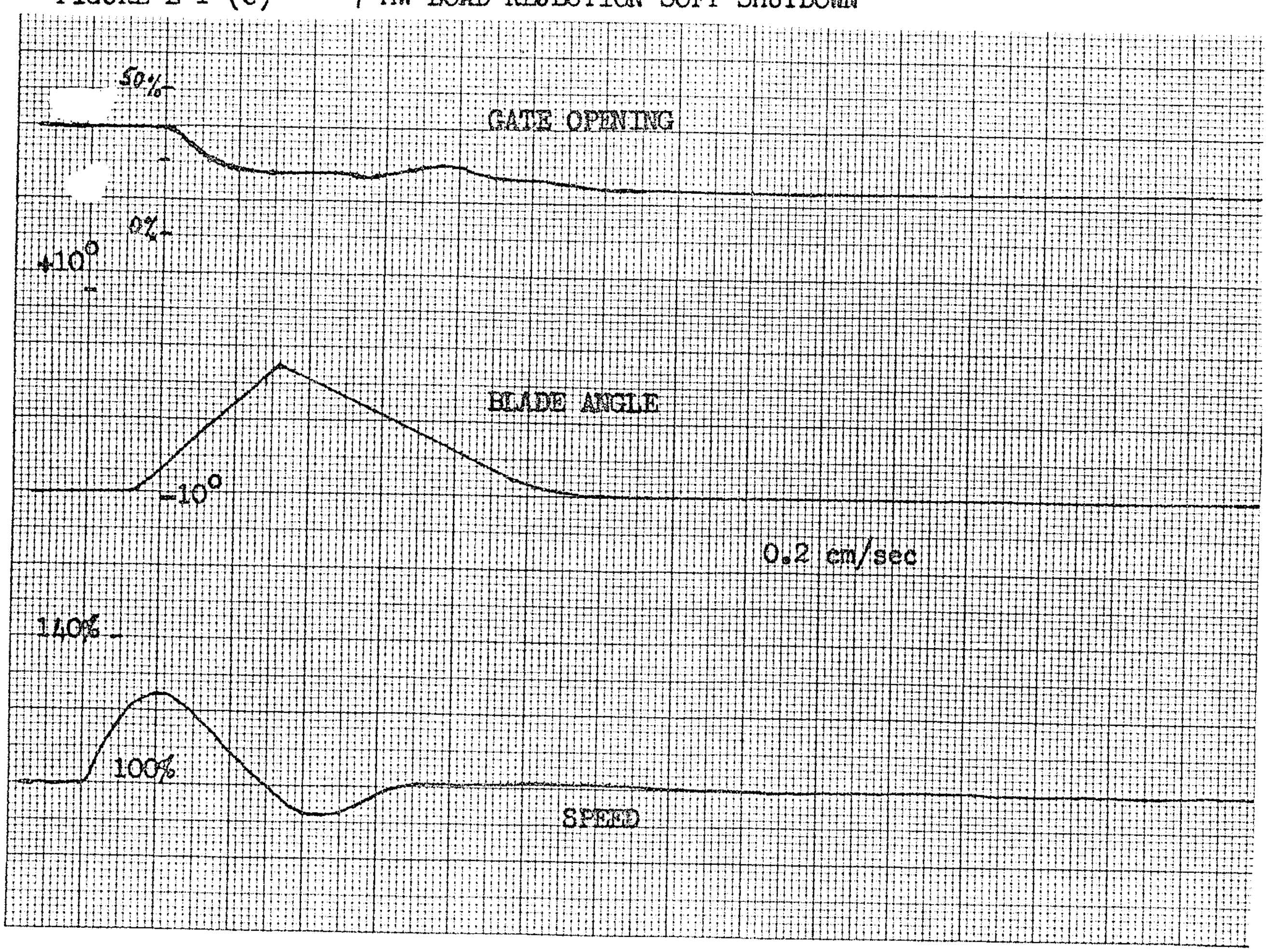


FIGURE E 1 (d) 7 MW LOAD REJECTION SOFT SHUTDOWN

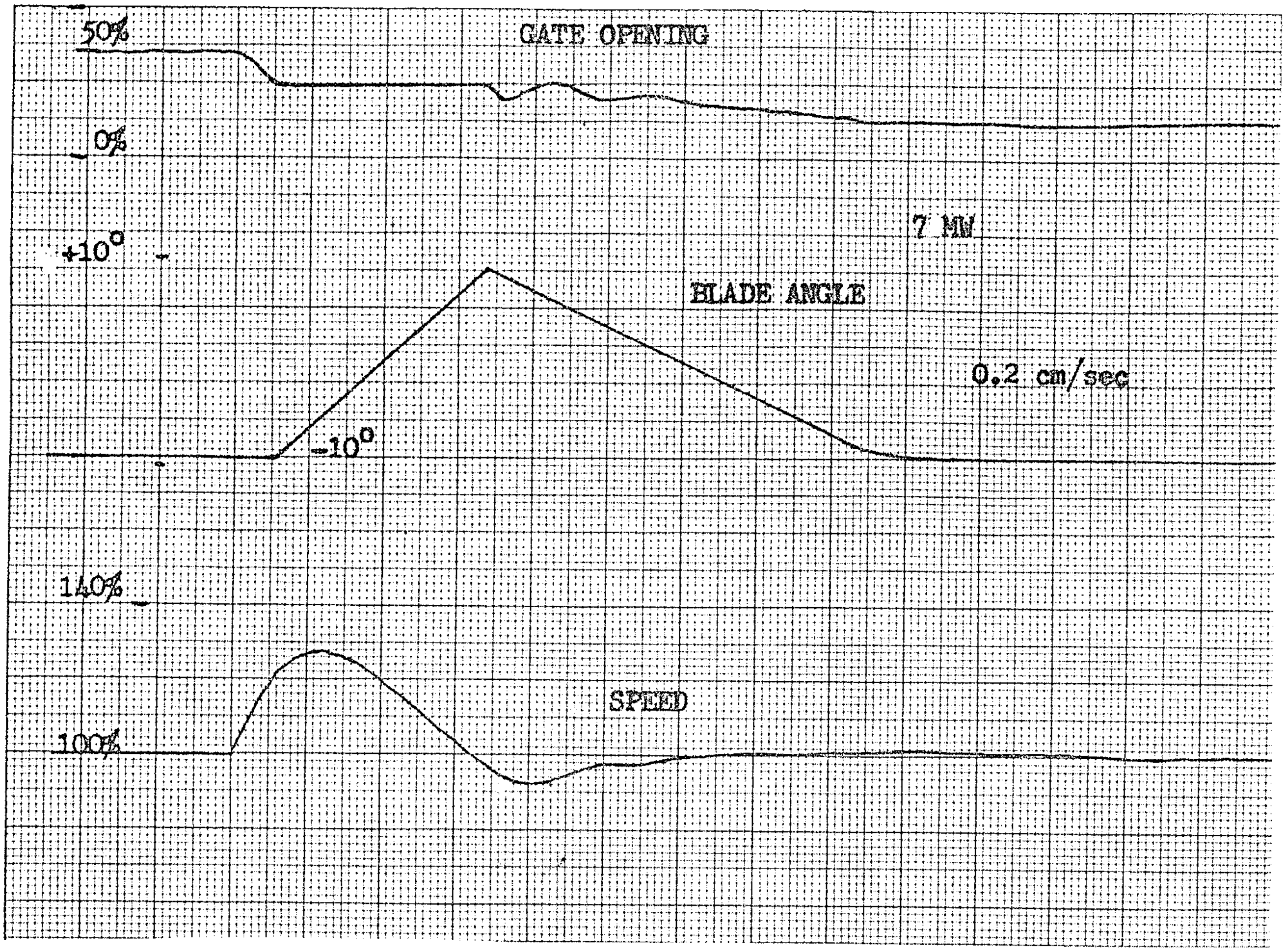


FIGURE E 1 (e) 7 MW LOAD REJECTION SOFT SHUTDOWN

LOAD REJECTION TESTS

TABLE E2

TEST NO.	% GATE AT SERVO	BLADE ANGLE AT OIL HEAD	MW BOARD METER	% GATE POSITION SWITCH SETTING	SNL LIMIT % GATE	START BLADE ANGLE DEGREES	PROGRAM CLOSING % GATE	PROGRAMED CLOSING ON SPEED	PROGRAMED CLOSING OFF SPEED	HWL FT	TWL FT	GROSS HEAD FT	PERMANENT DROOP B_p (POS)	TEMPORARY DROOP B_t (POS) * **	TEMPORARY DROOP TIME CONST (POS) * **	DERIVATIVE TIME CONST T_n SEC	MVAR	FIELD VOLTS	FIELD AMPS	STATOR VOLTS	STATOR AMPS	TYPE LOAD REJECTION	REMARKS GOVERNOR CONTROL
a	59	+4.8°	14.3	22	20	+10	25	120	98	703.9	679.5	24.4	5	9/9	3/3	0.05	5.0	200	1625	4200	2000	Soft	
b	57	+2.5°	14.5	22	20	+10	25	120	98	704.8	679.3	25.5	5	9/9	3/3	0.05	3.0	200	1675	4300	2050	Soft	SNL IN SERVICE
c	56	+2.1°	14.5	22	20	+10	25	120	98	704.9	679.3	25.6	5	9/9	3/3	0.05	3.0	180	1560	4250	2000	Soft	SNL IN SERVICE
d	56	+2.0°	14	5	SNL OUT	+10	20	120	100	705.2	679.3	25.9	5	9/9	3/3	0.05	3.0	180	1500	4200	2000	Soft	SNL OUT OF SERVICE
e	55	+1.1°	14	5	SNL OUT	+10	22.5	120	100	705.2	679.2	26.0	5	9/9	3/3	0.05	3.5	180	1550	4250	2000	Soft	SNL OUT OF SERVICE
f	56	+1.8°	14.5	5	SNL OUT	+10	22.5	120	100	705.2	679.4	25.8	5	9/9	4/3	0.05	4.0	200	1600	4250	2000	Soft	SNL OUT OF SERVICE
g	56	+2.1°	14	35	25	+10	29.7	120	100	705.0	679.5	25.5	5	9/9	3/3	0.05	1.0	175	1400	4200	2000	Soft	
h	55	+1.0°	14	35	25	+10	29.7	120	99	705.2	679.5	25.7	5	9/9	3/3	0.05	3.0	180	1500	4200	2000	Soft	
i	52.8	+0.6°	14	35	23.5	+10.2	29.7	120	99	706.3	680.1	26.2	5	9/9	3/3	0.05	2.5	175	1450	4200	2000	Soft	
j	35	-4.0°	14	35	11	-10	29.7	120	99	713.4	676.4	37.0	5	9/9	3/3	0.05	3.0	180	1500	4200	2000	Soft	

* —NO LOAD VALUES
** —ON LINE VALUES
HWL—FOREBAY WATER LEVEL
TWL—TAILRACE WATER LEVEL
SNL—SPEED NO LOAD

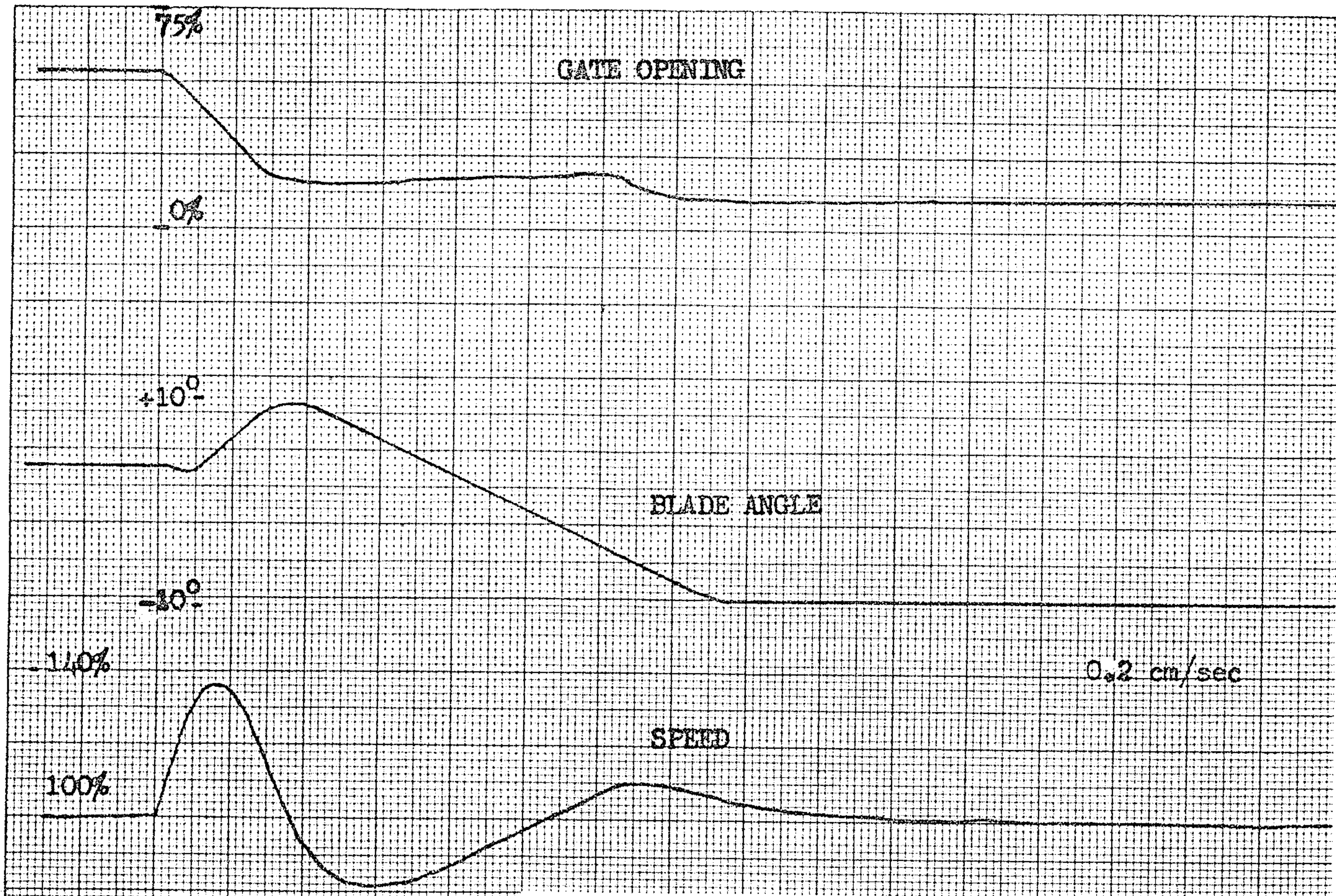


FIGURE E 2 (a)

14 MW LOAD REJECTION SOFT SHUTDOWN

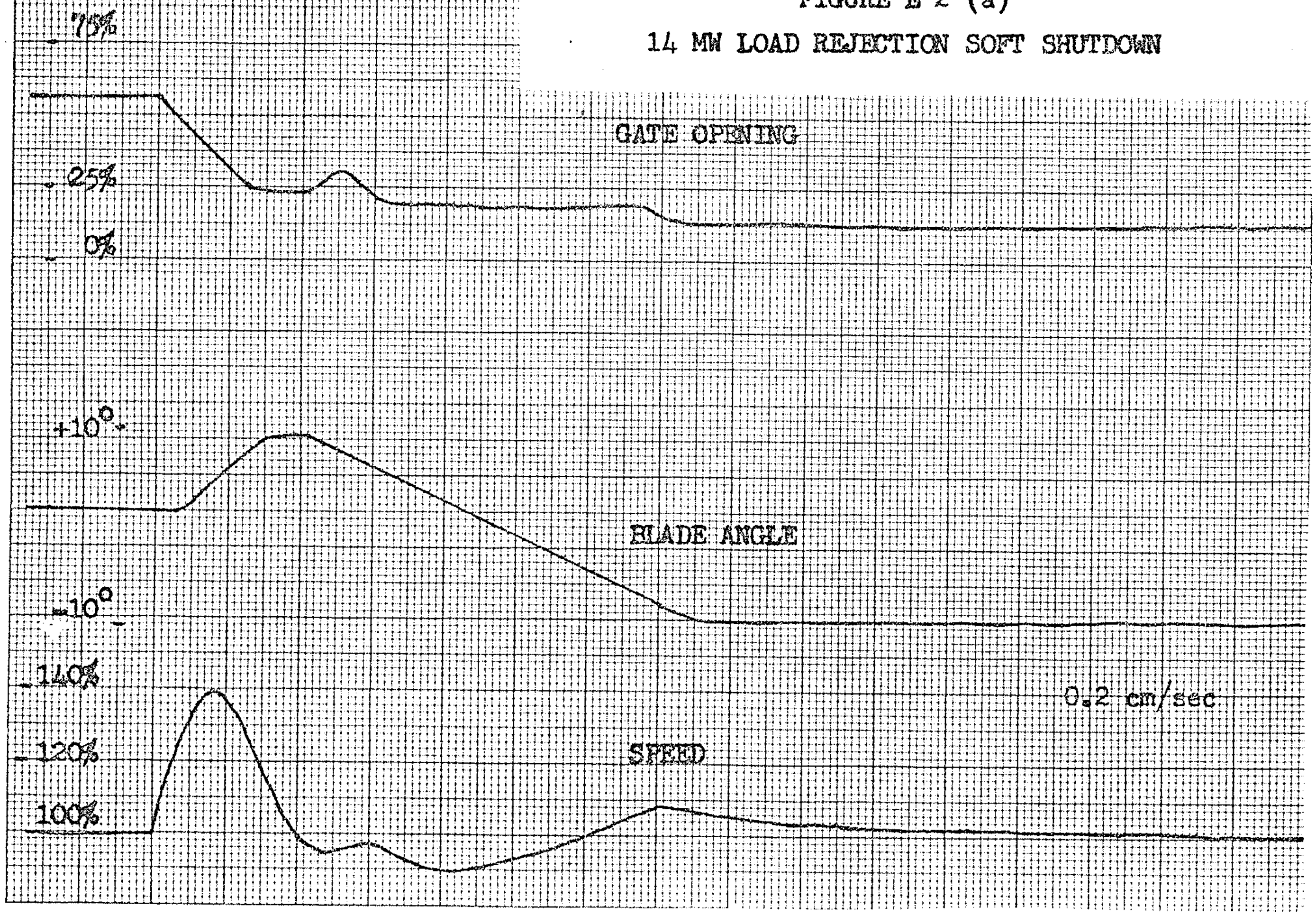


FIGURE E 2 (b)

14 MW LOAD REJECTION SOFT SHUTDOWN

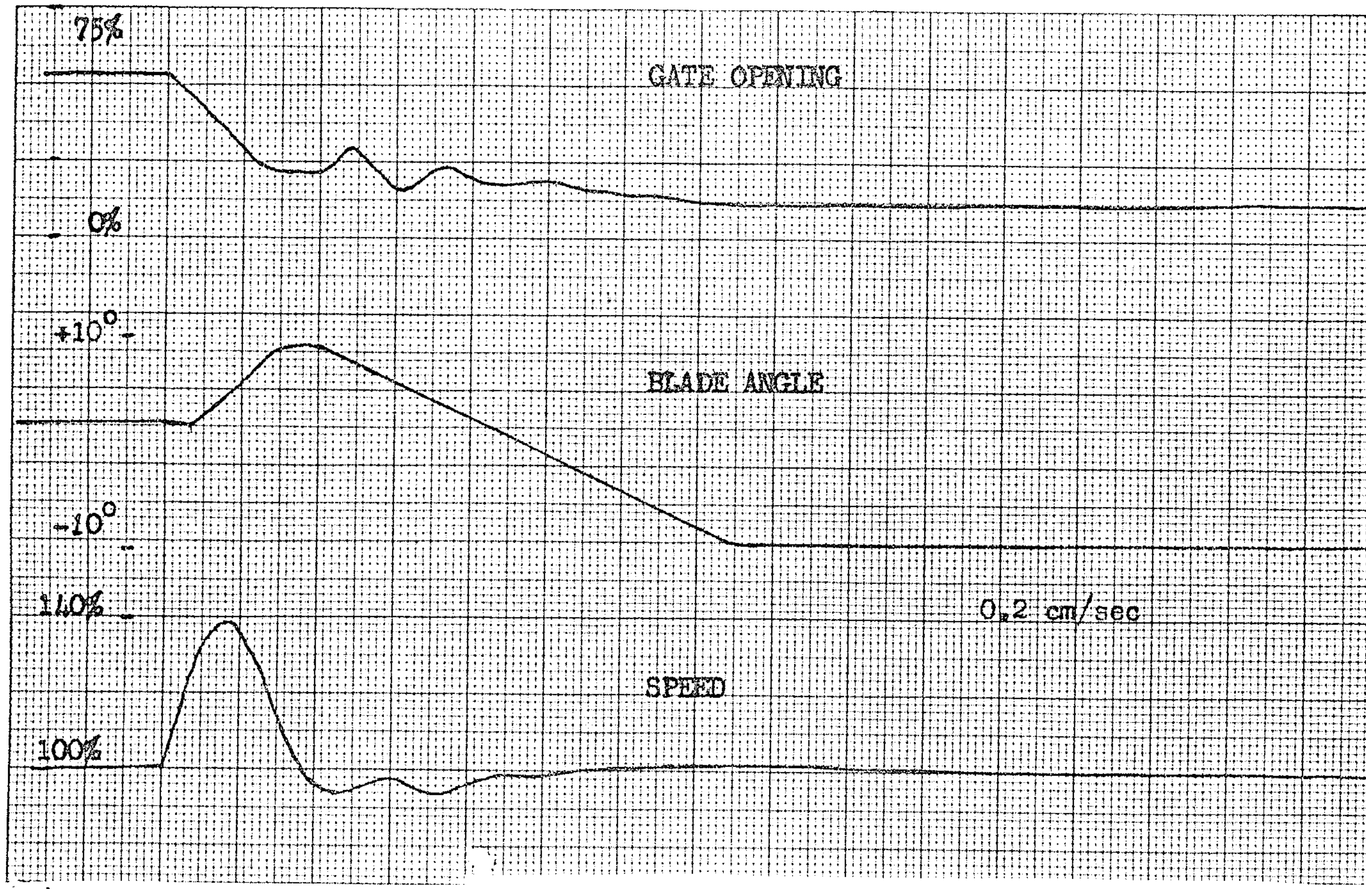


FIGURE E 2 (c)

14 MW LOAD REJECTION SOFT SHUTDOWN

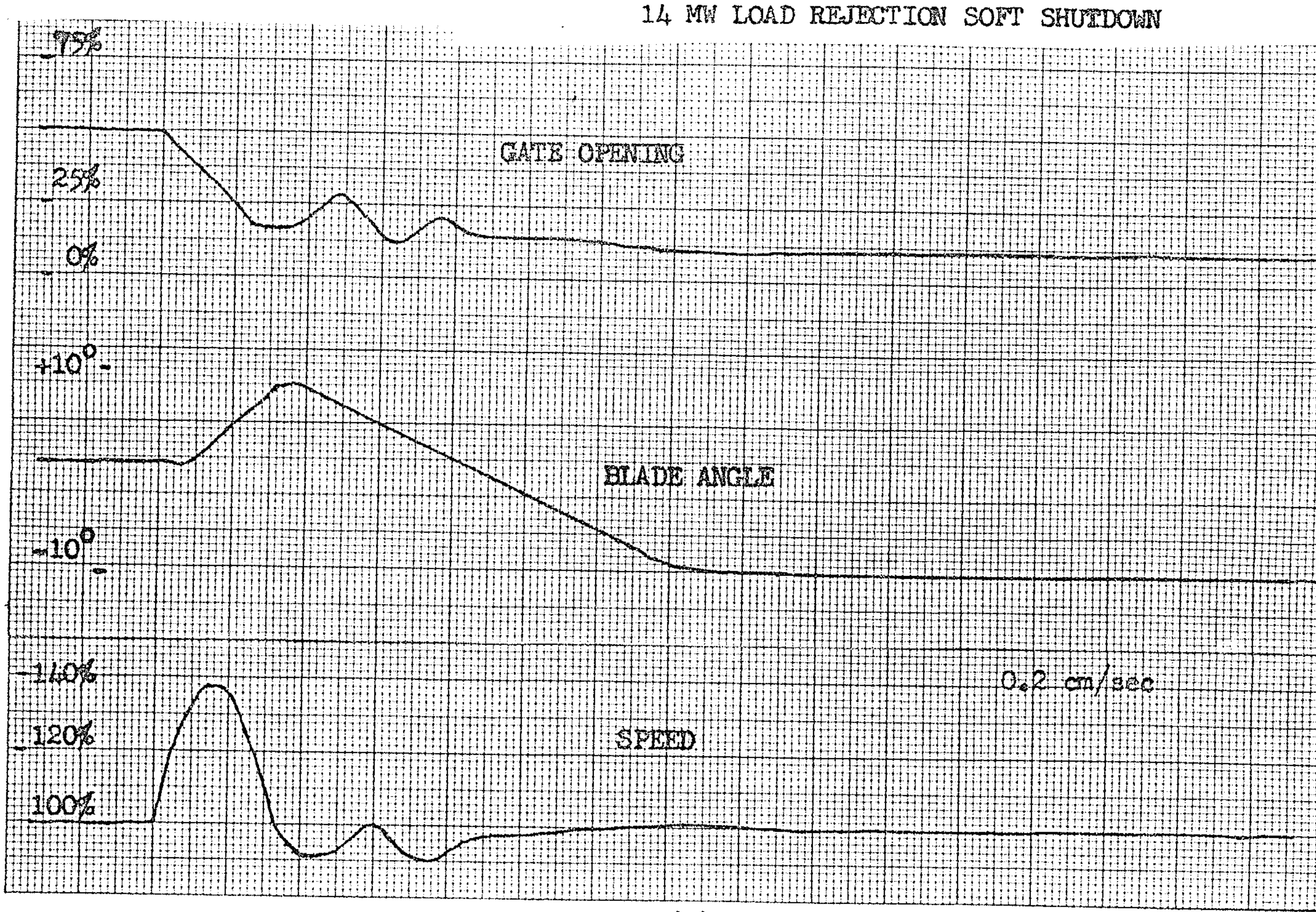


FIGURE E 2 (d)

14 MW LOAD REJECTION SOFT SHUTDOWN

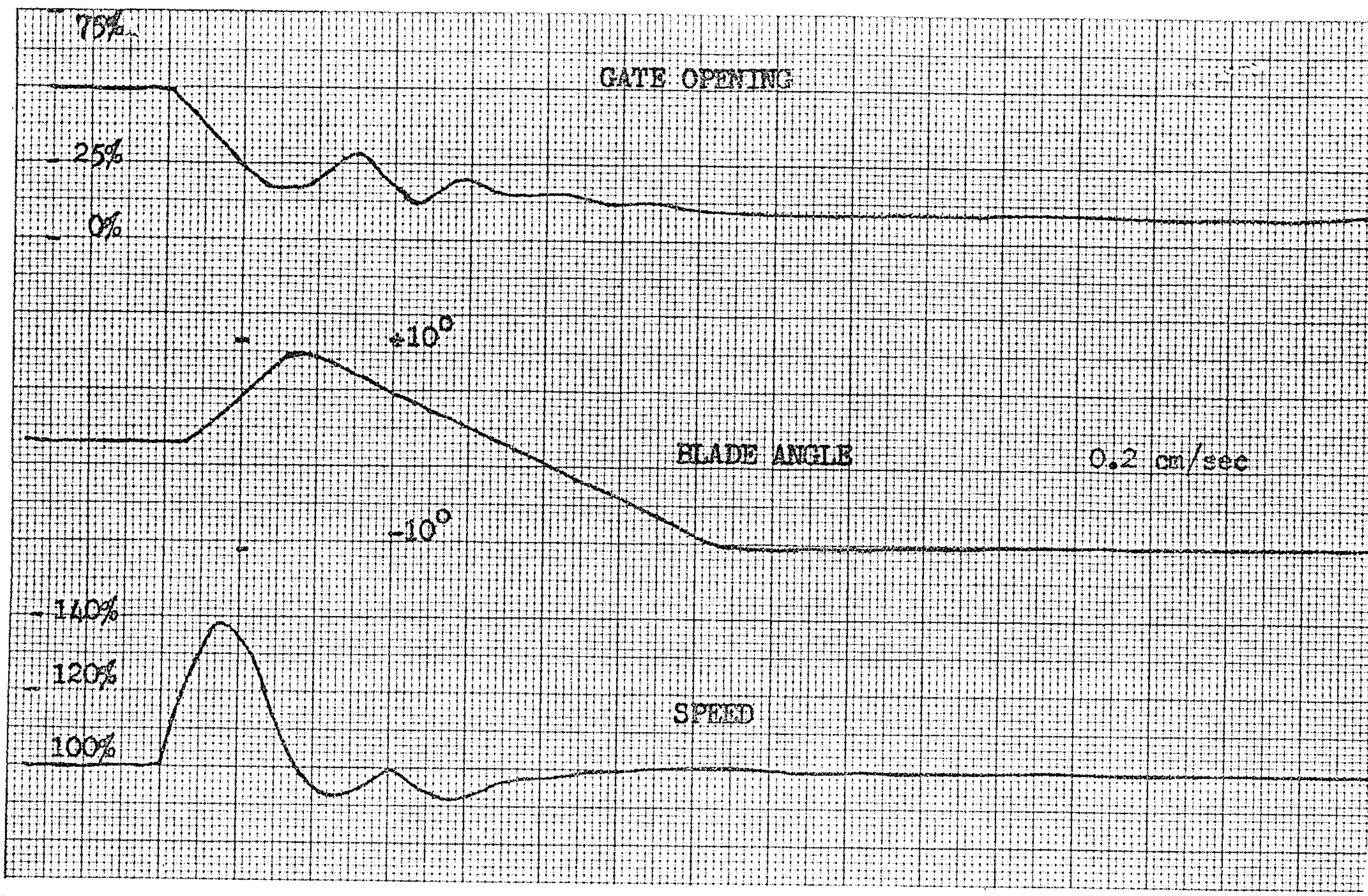


FIGURE E 2 (e)

14 MW LOAD REJECTION SOFT SHUTDOWN

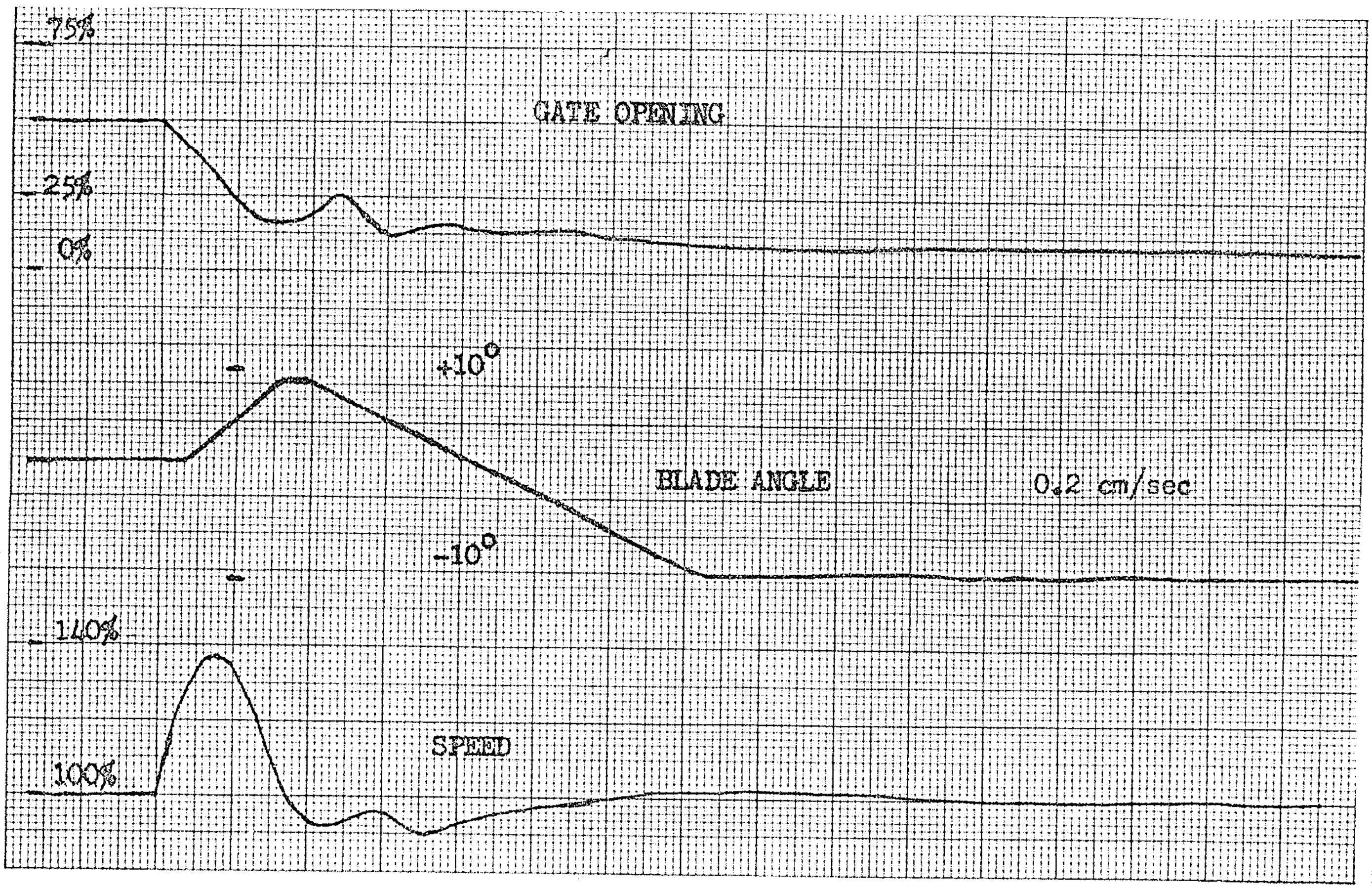


FIGURE E 2 (f)

14 MW LOAD REJECTION SOFT SHUTDOWN

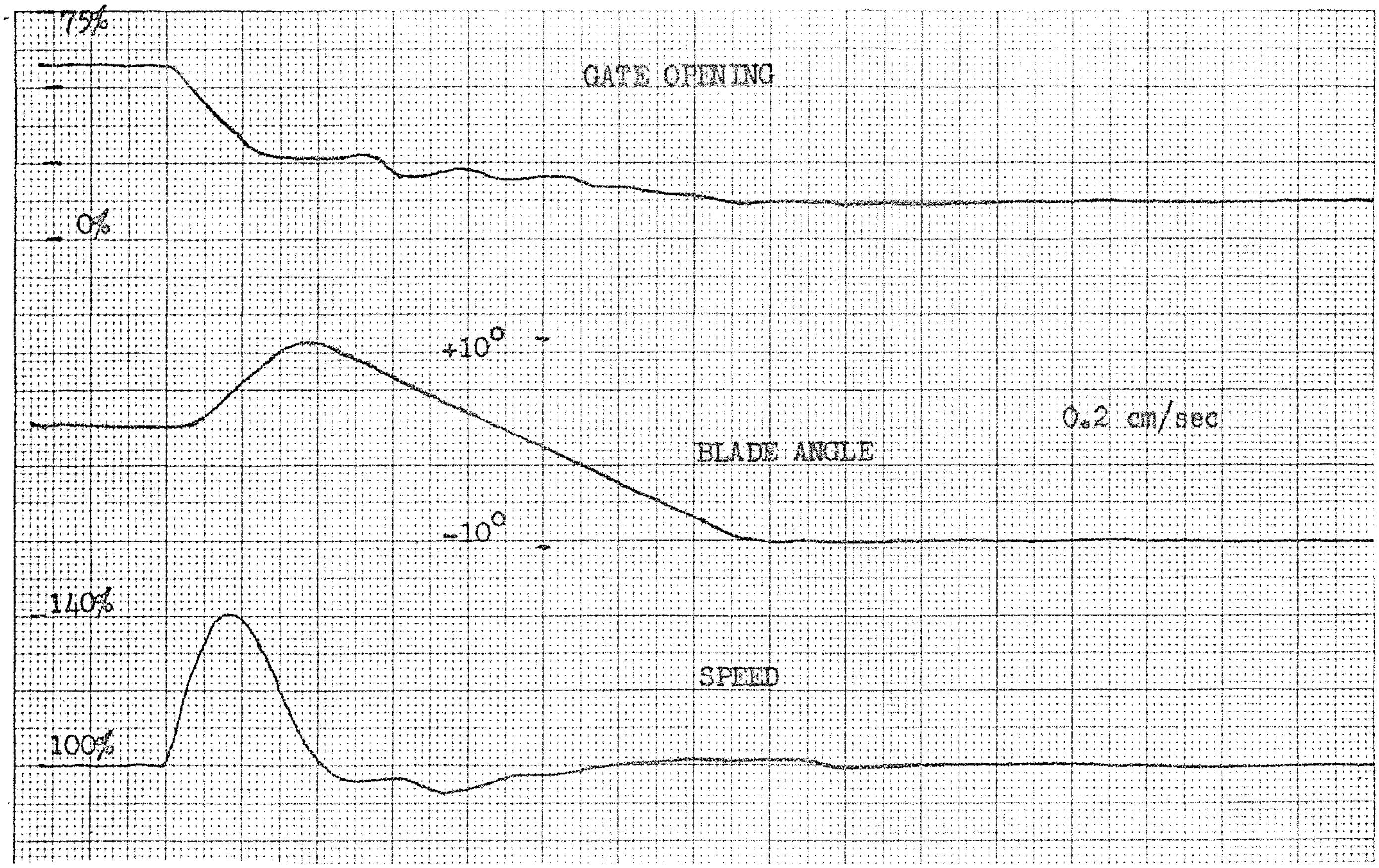


FIGURE E 2 (g)

14 MW LOAD REJECTION SOFT SHUTDOWN

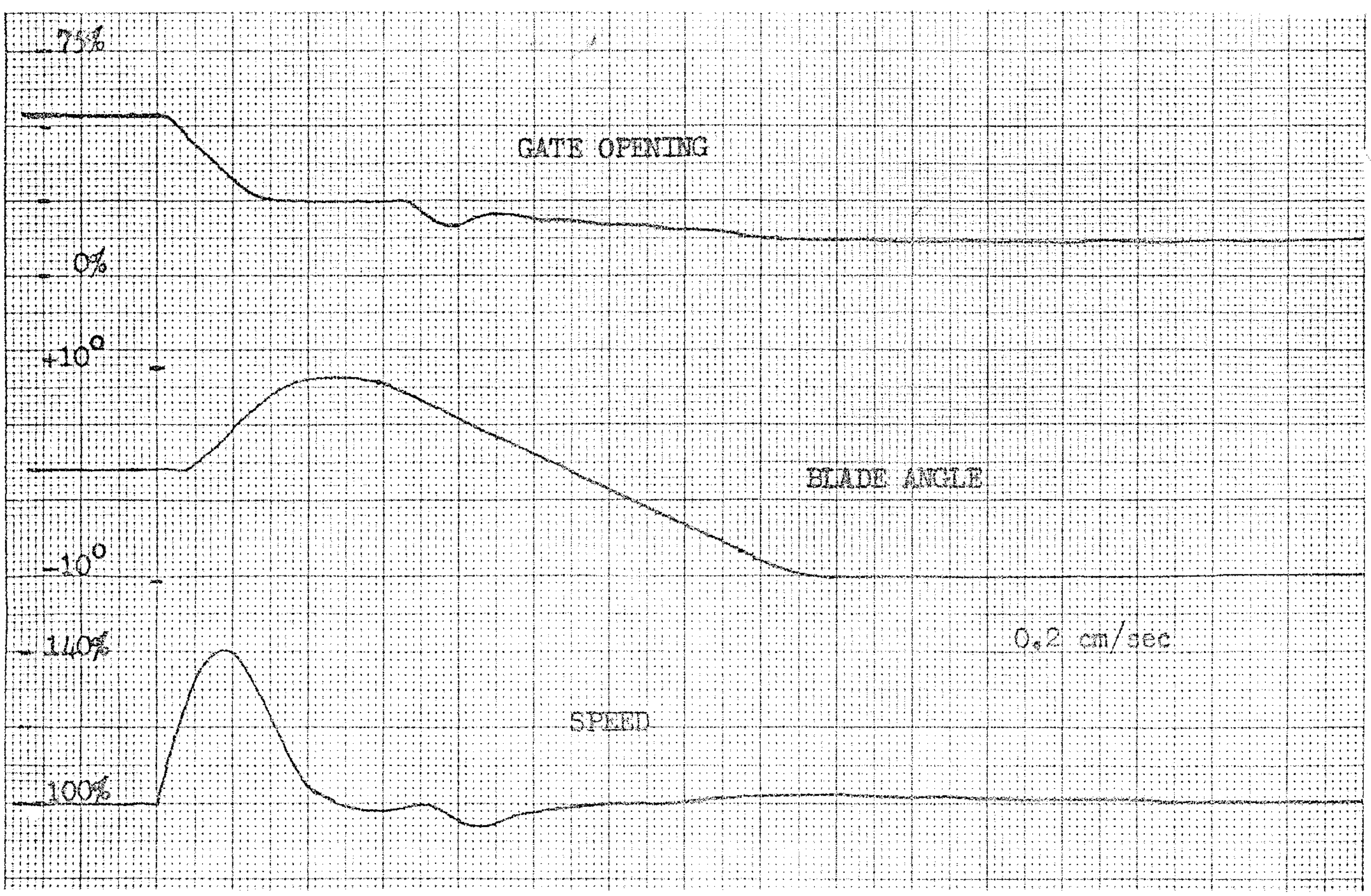


FIGURE E2 (h)

14 MW LOAD REJECTION SOFT SHUTDOWN

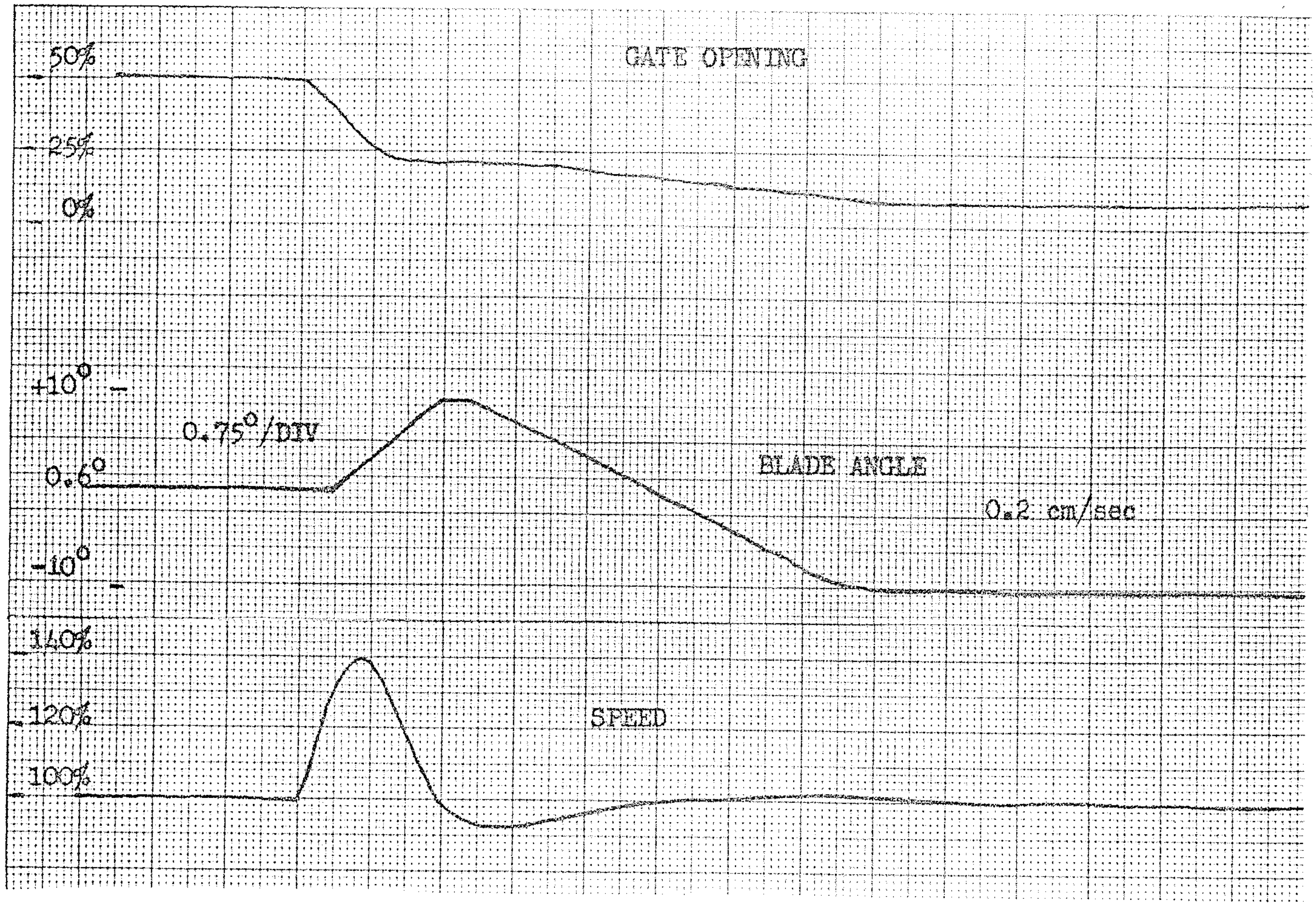


FIGURE E 2 (i)

14 MW LOAD REJECTION SOFT SHUTDOWN

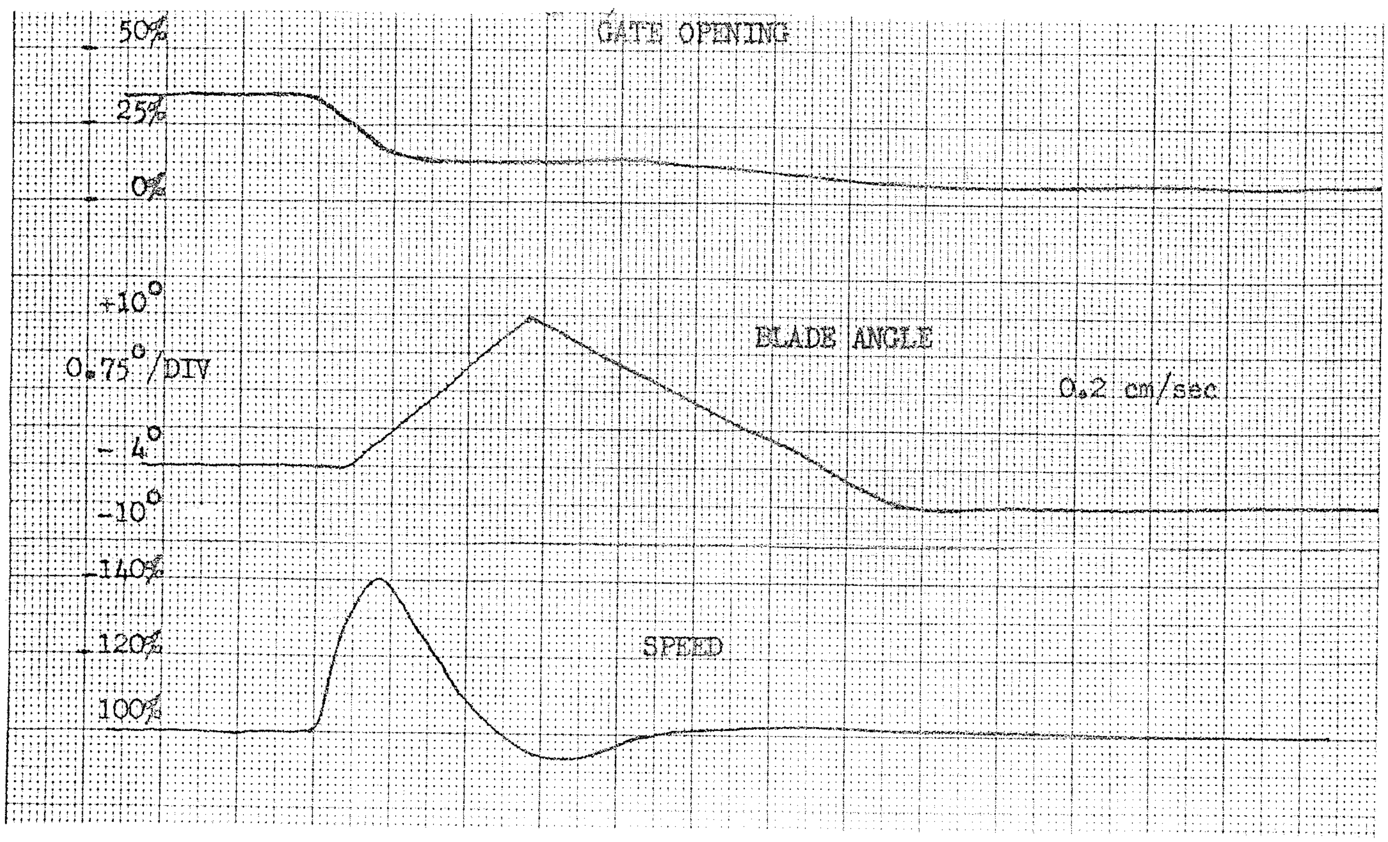


FIGURE E2 (j)

14 MW LOAD REJECTION SOFT SHUTDOWN

LOAD REJECTION TESTS

TABLE E 3

EST NO.	% GATE AT SERVO	BLADE ANGLE AT OIL HEAD	MW BOARD METER	% GATE POSITI-ON SWITCH SETT-ING	SNL LIMIT % GATE	START BLADE ANGLE DEGR-EES	PROG-RAM CLOS-ING % GATE	PROGRAMED CLOSING ON SPEED	PROGRAMED CLOSING OFF SPEED	HWL FT	TWL FT	GROSS HEAD FT	PERM-ANENT DROOP B_p (POS)	TEMPO-RARY DROOP B_t (POS) * **	TEMPO-RARY DROOP TIME CONST (POS) * **	DERIVA-TIVE TIME CONST T_n SEC	MVAR	FIELD VOLTS	FIELD AMPS	STATOR VOLTS	STATOR AMPS	TYPE LOAD REJEC-TION	REMARKS GOVERNOR CONTROL
a	76	+12.8	21	22	20	+10	25	120	98	704.8	679.32	25.48	5	9/9	3/3	0.05	3	200	1625	4225	2900	Soft	SNL DISCONNECTE
b	74	+12.0	21	5	SNL OUT	+10	22.5	120	100	704.95	679.21	25.74	5	9/9	4/3	0.05	4	200	1700	4250	2900	Soft	SNL DISCONNECTE
c	72.5	+11.8	21.5	35	25	+10	29.7	120	99	705.11	679.4	25.71	5	9/9	3/3	0.05	2	200	1550	4200	2950	Soft	
d	71	+11.5	21	35	23.5	+10	29.7	120	99	705.32	679.5	25.82	5	9/9	3/3	0.05	3	200	1600	4200	2850	Soft	
e	46	+ 1.3	21	35	11	-10	29.7	120	99	713.48	676.27	37.21	5	9/9	3/3	0.05	3.5	200	1600	4200	2800	Soft	

* —NO LOAD VALUES
** —ON LINE VALUES
HWL—FOREBAY WATER LEVEL
TWL—TAILRACE WATER LEVEL
SNL—SPEED NO LOAD

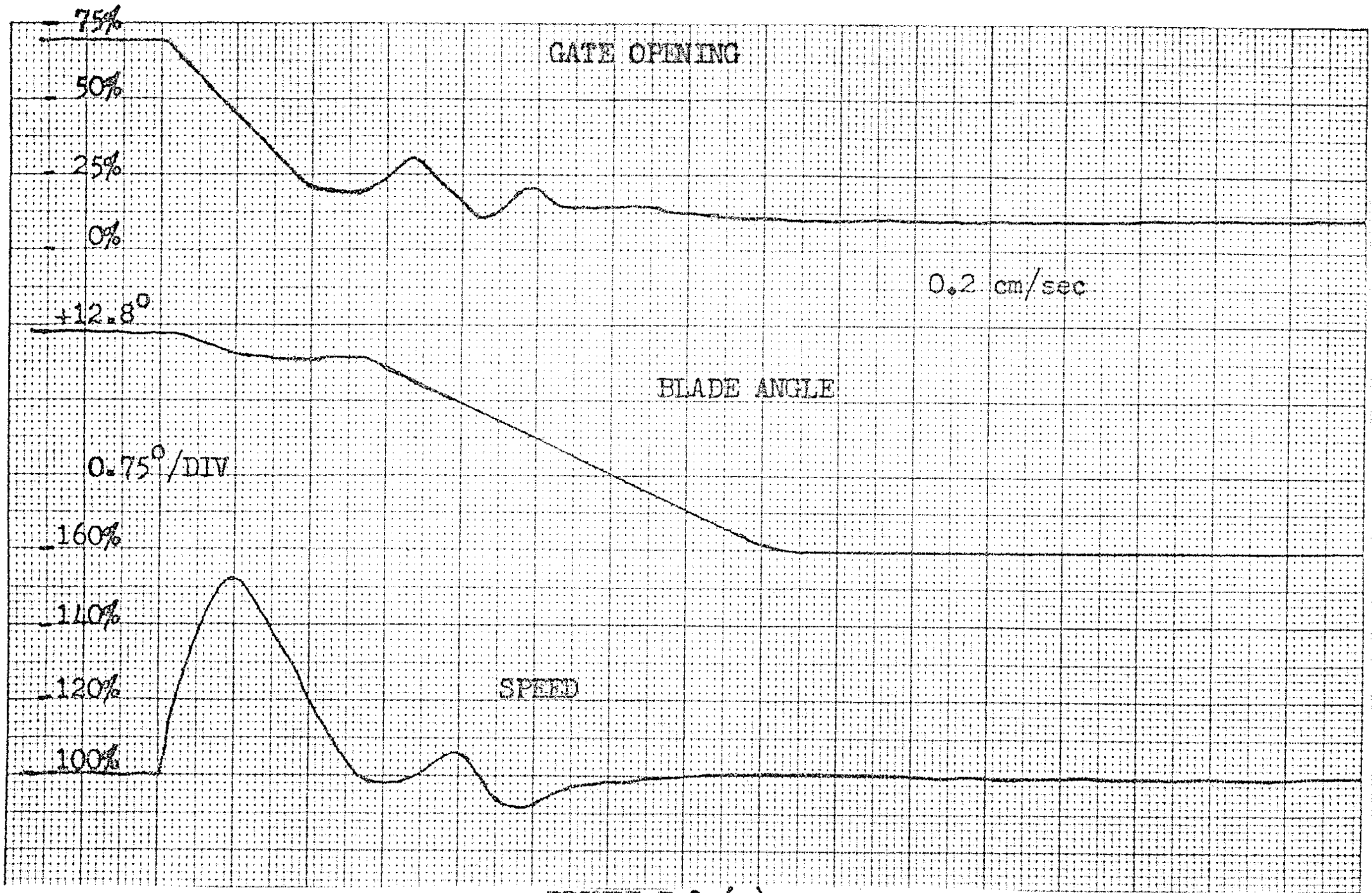


FIGURE E 3 (a)

21 MW LOAD REJECTION SOFT SHUTDOWN

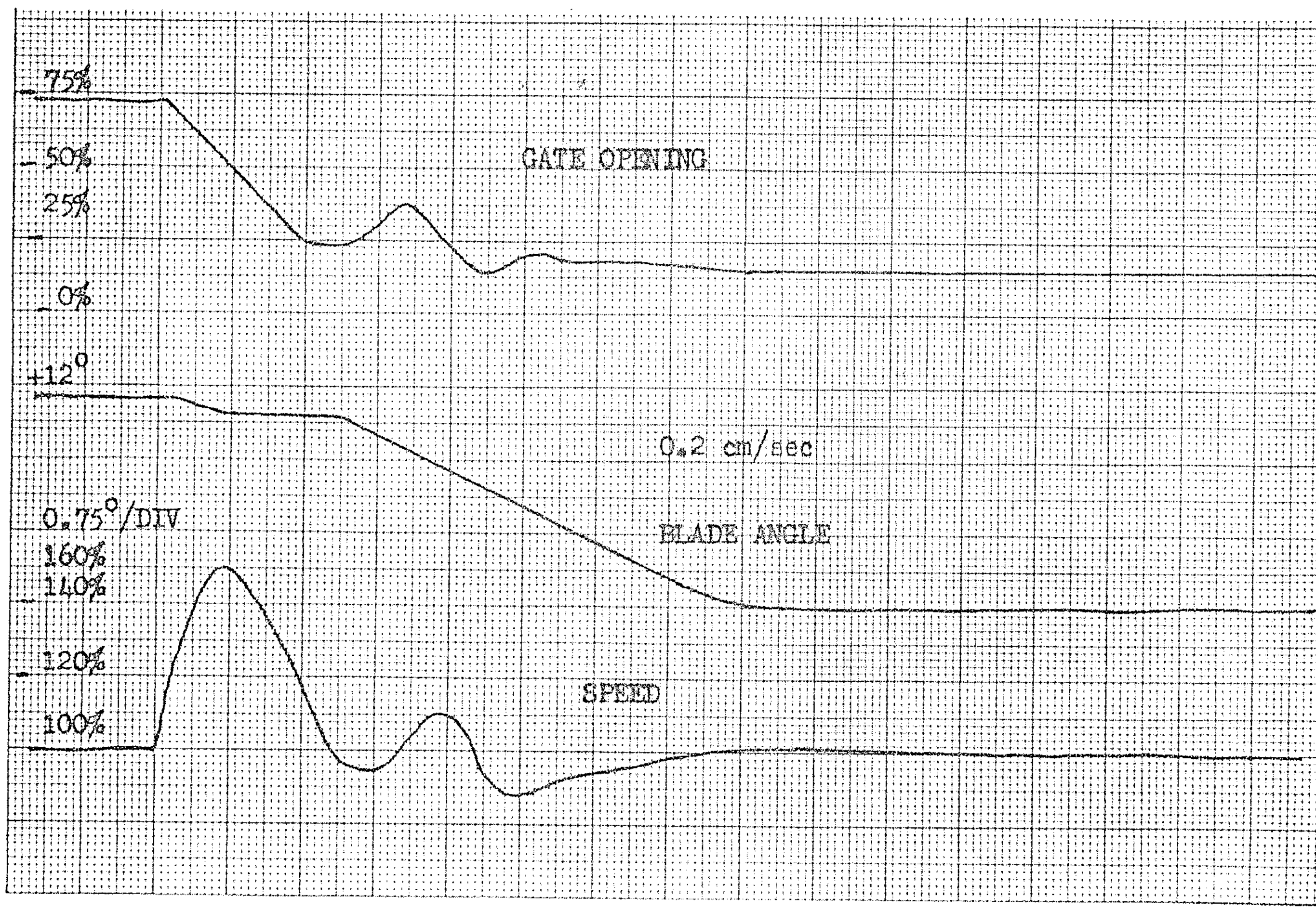


FIGURE E3 (b)

21 MW LOAD REJECTION SOFT SHUTDOWN

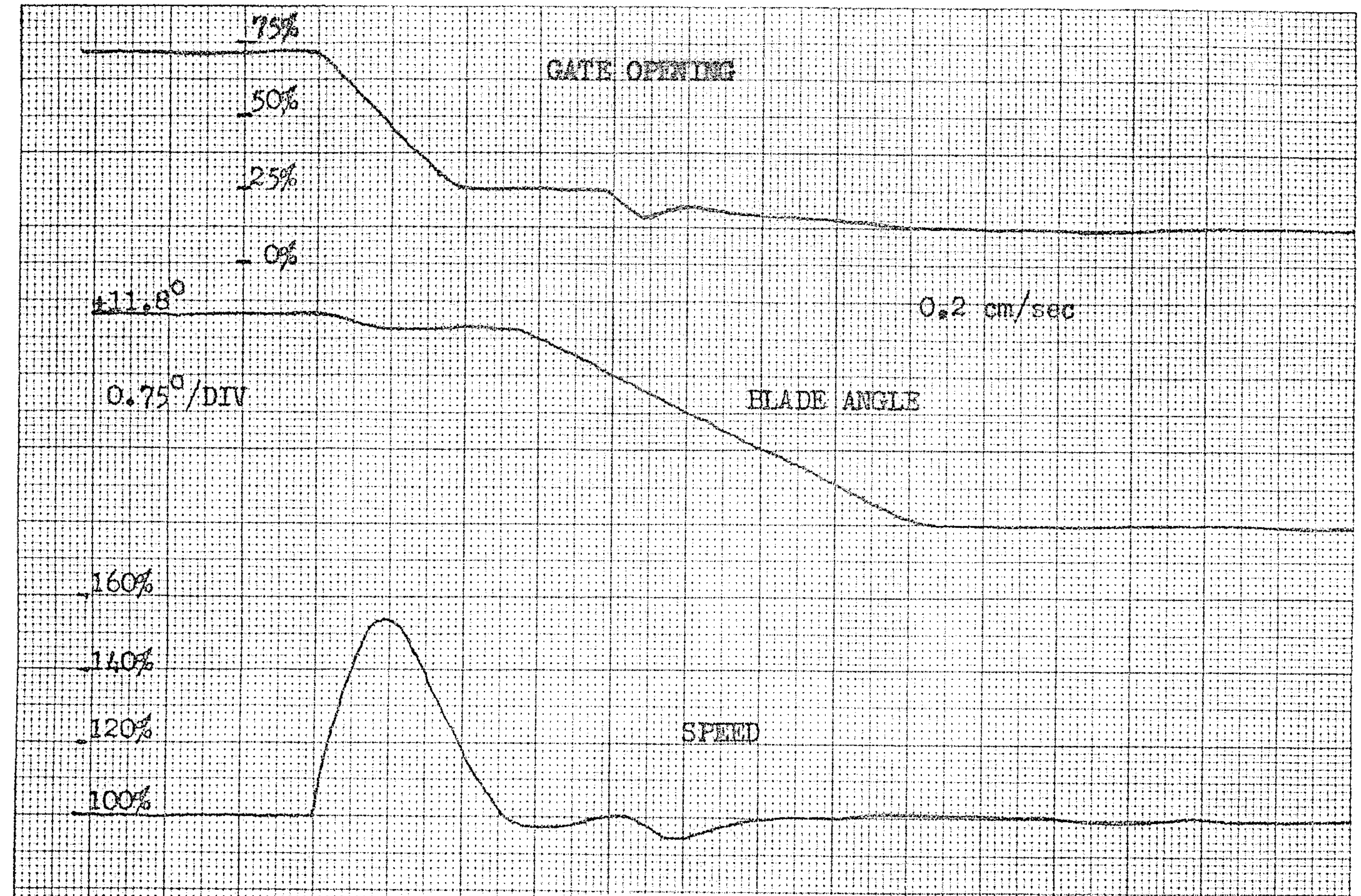


FIGURE E 3 (c)

21.5 MW LOAD REJECTION SOFT SHUTDOWN

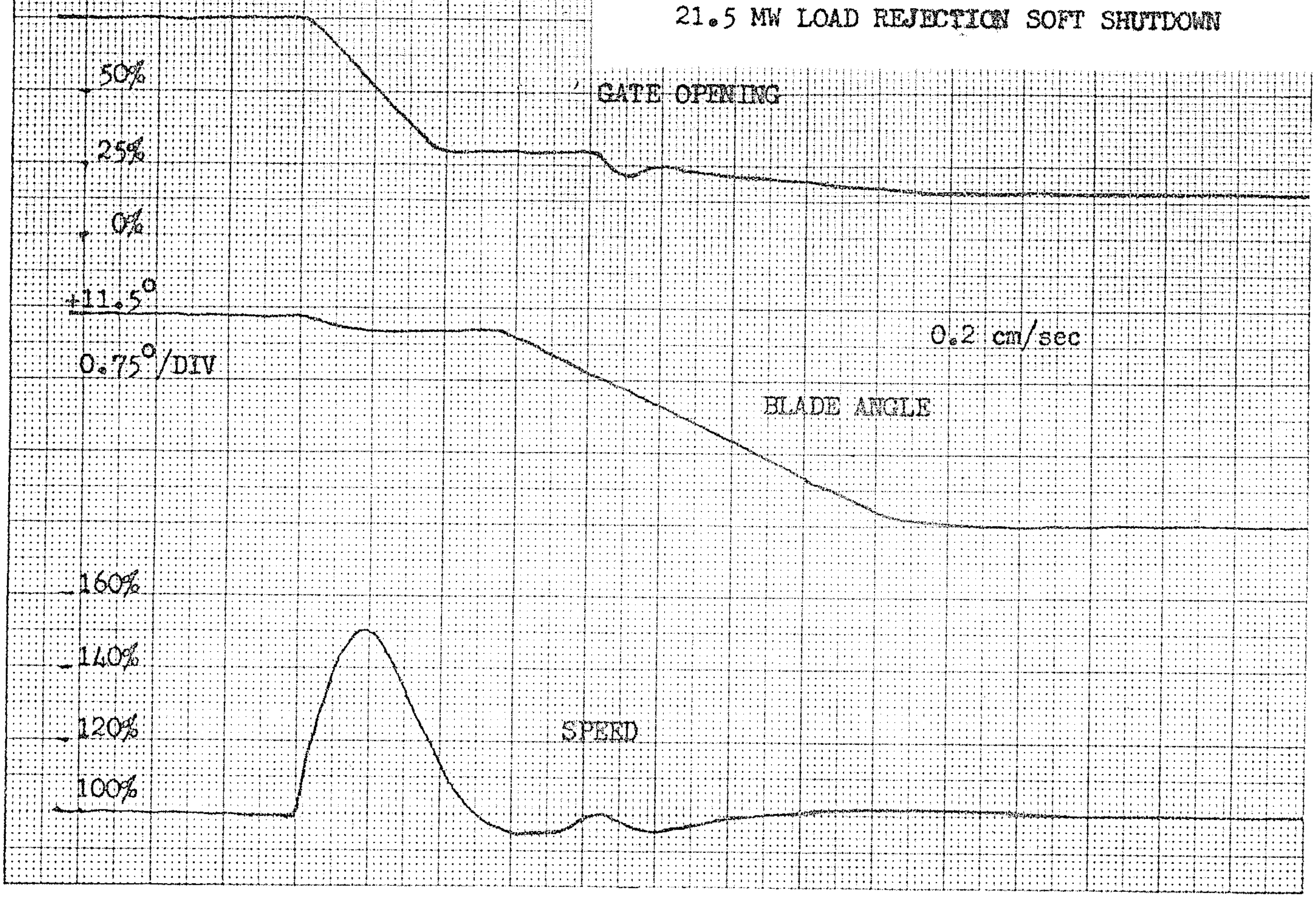


FIGURE E3 (d)

21 MW LOAD REJECTION SOFT SHUTDOWN

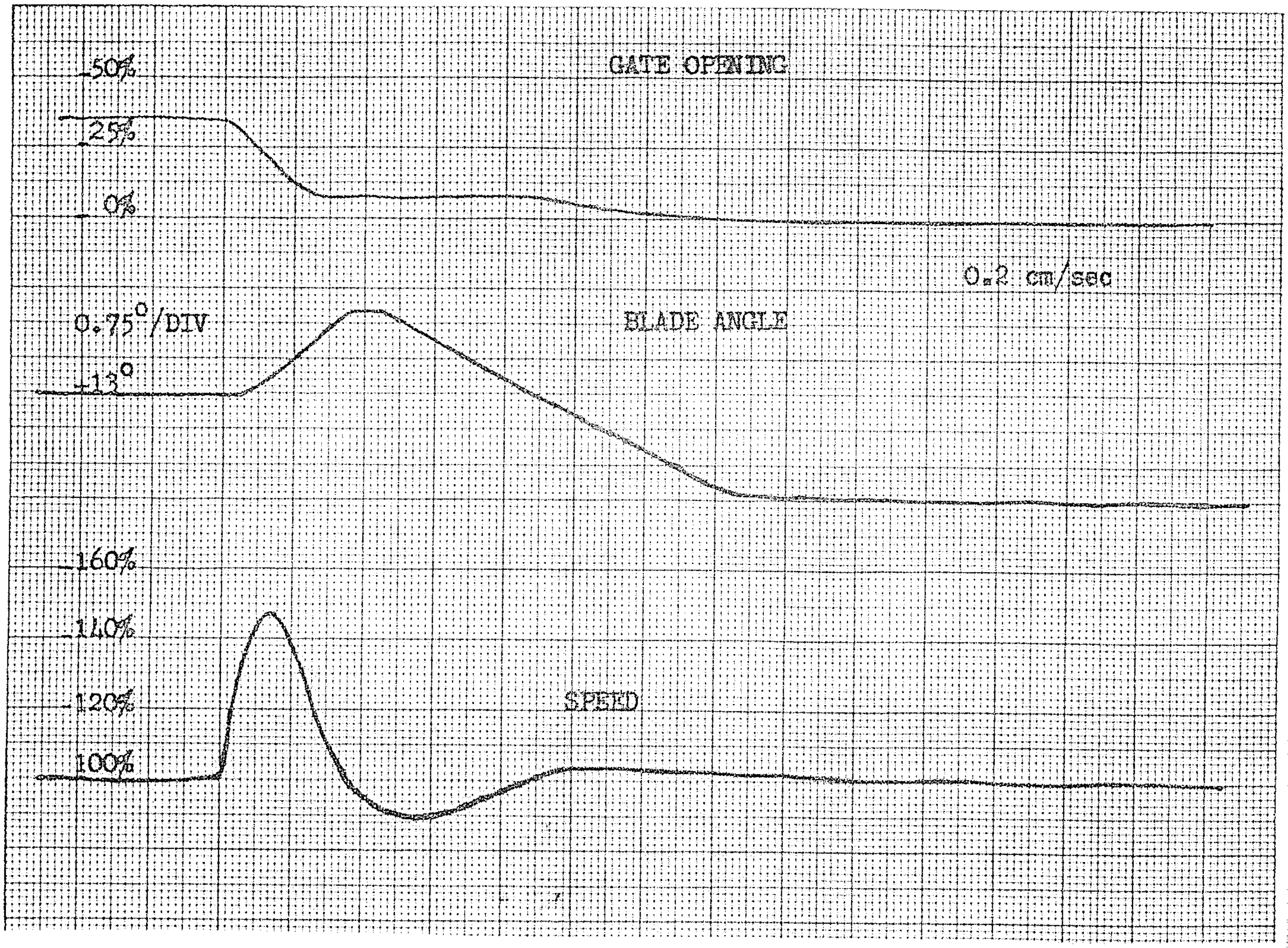


FIGURE E 3 (e)

21 MW LOAD REJECTION SOFT SHUTDOWN

LOAD REJECTION TESTS

TABLE E 4

EST NO.	% GATE AT SERVO	BLADE ANGLE AT OIL HEAD	MW BOARD METER	% GATE POSITI-ON SWITCH SETT-ING	SNL LIMIT % GATE	START BLADE ANGLE DEGR-EES	PROG-RAM CLOS-ING % GATE	PROGRAMED CLOSING ON SPEED	PROGRAMED CLOSING OFF SPEED	HWL FT	TWL FT	GROSS HEAD FT	PERM-ANENT DROOP B_p (POS)	TEMPO-RARY DROOP B_t (POS) * **	TEMPO-RARY DROOP TIME CONST (POS) * **	DERIVA-TIVE TIME CONST T_n SEC	MVAR	FIELD VOLTS	FIELD AMPS	STATOR VOLTS	STATOR AMPS	TYPE LOAD REJEC-TION	REMARKS GOVERNOR CONTROL
a	94.5	+19.4°	27.5	5	SNL OUT	+10	22.5	120	100	705.0	679.25	25.75	5	9/9	3/3	0.05	5	225	1900	4250	3800	Soft	
b	92	+18.8	28.2	35	25	+10	29.7	120	99	704.8	679.88	24.92	5	9/9	3/3	0.05	2.5	200	1750	4200	3900	Soft	
c	57.5	+ 9.8	28	35	11	-10	29.7	120	99	713.43	676.47	36.96	5	9/9	3/3	0.05	3	200	1750	3950	3950	Soft	

* —NO LOAD VALUES
** —ON LINE VALUES
HWL—FOREBAY WATER LEVEL
TWL—TAILRACE WATER LEVEL
SNL—SPEED NO LOAD

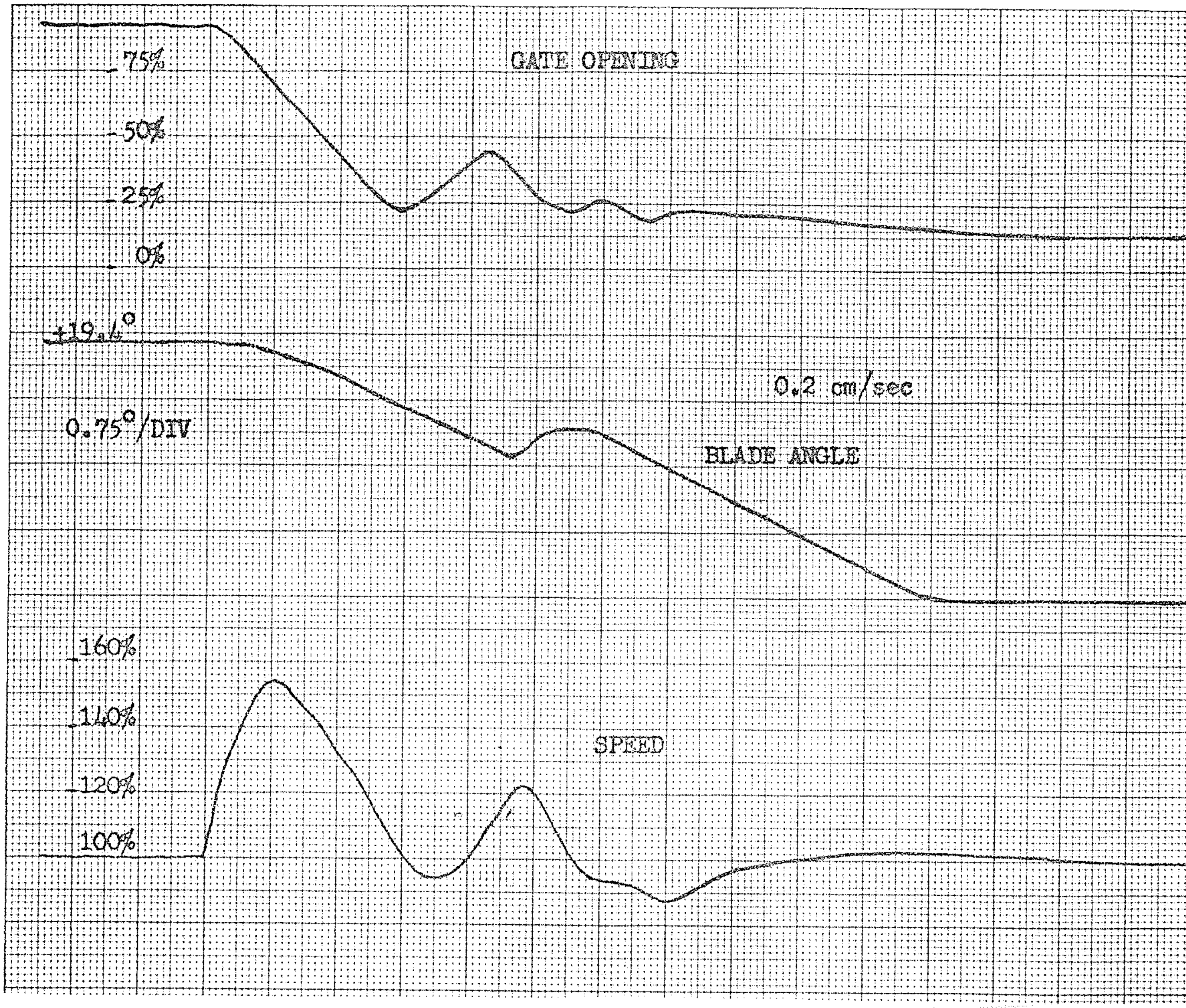


FIGURE E 4 (a)

28 MW LOAD REJECTION SOFT SHUTDOWN

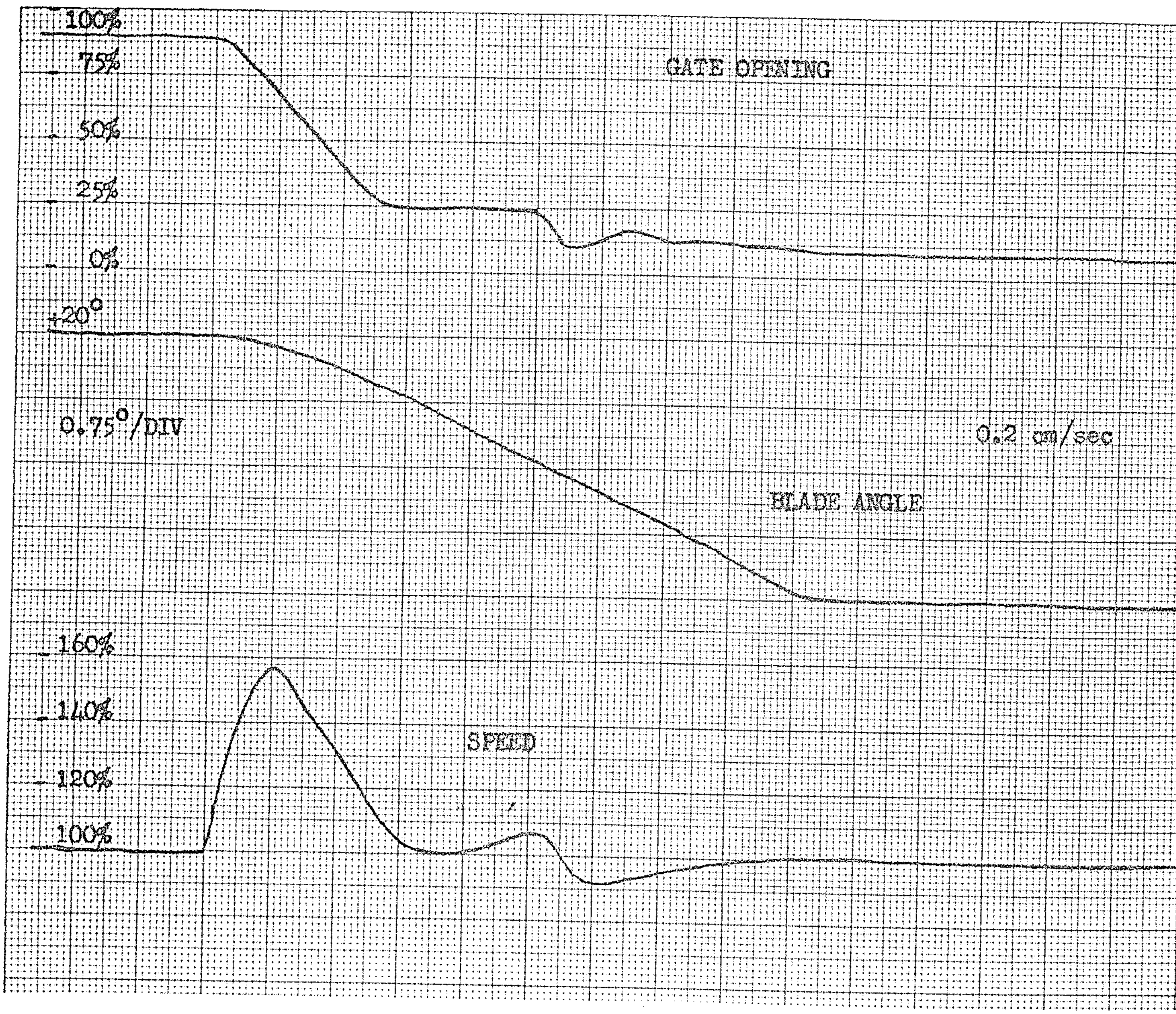


FIGURE E 4 (b)

28 MW LOAD REJECTION SOFT SHUTDOWN

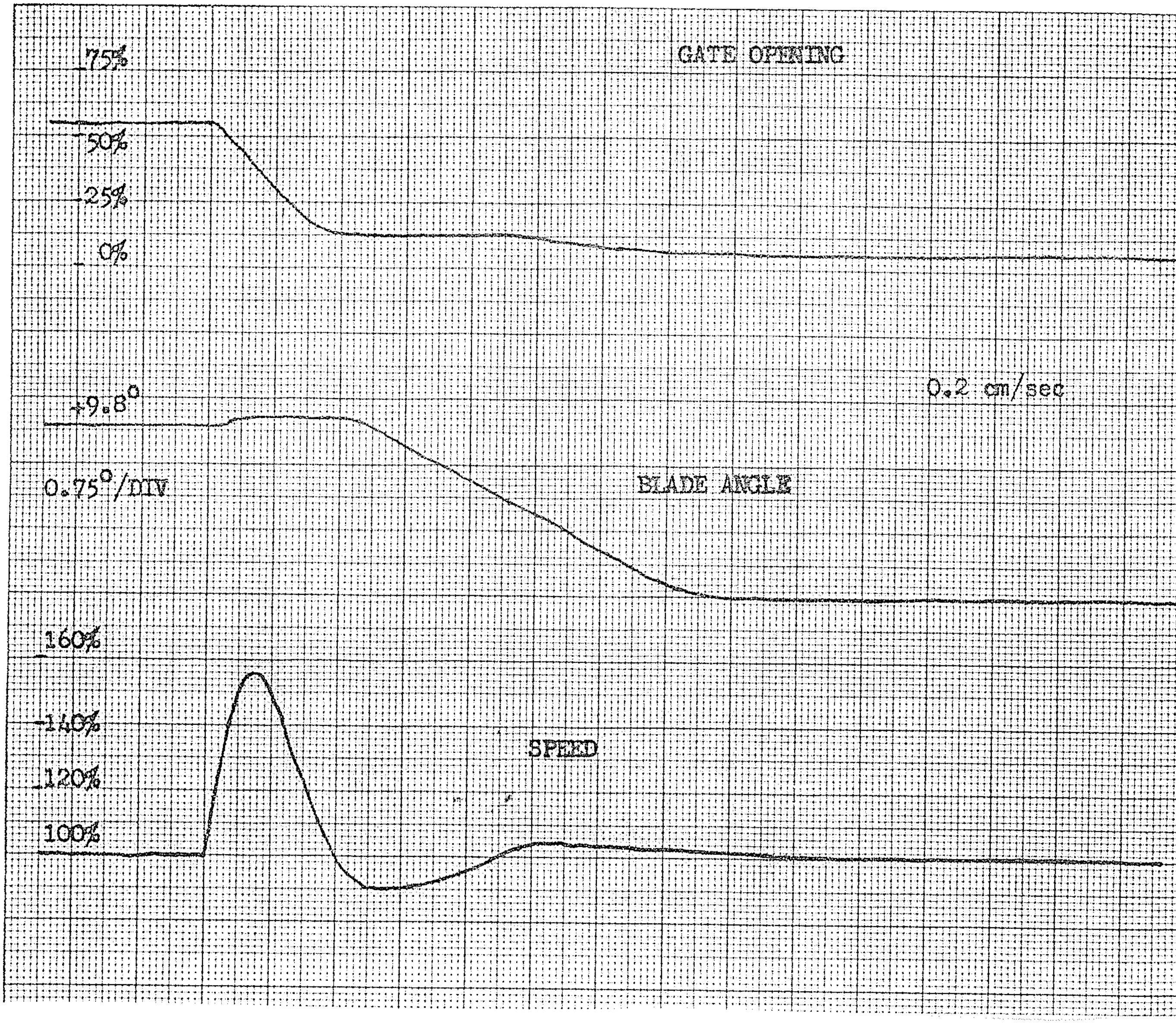


FIGURE E 4 (c)
28 MW LOAD REJECTION SOFT SHUTDOWN

LOAD REJECTION TESTS

TABLE E 5

EST NO.	% GATE AT SERVO	BLADE ANGLE AT OIL HEAD	MW BOARD METER	% GATE POSITION SWITCH SETTING	SNL LIMIT % GATE	START BLADE ANGLE DEGREES	PROGRAM CLOSING % GATE	PROGRAMED CLOSING ON SPEED	PROGRAMED CLOSING OFF SPEED	HWL FT	TWL FT	GROSS HEAD FT	PERMANENT DROOP B_p (POS)	TEMPORARY DROOP B_t (POS) * **	TEMPORARY DROOP TIME CONST (POS) * **	DERIVATIVE TIME CONST T_n SEC	MVAR	FIELD VOLTS	FIELD AMPS	STATOR VOLTS	STATOR AMPS	TYPE LOAD REJECTION	REMARKS
																							GOVERNOR CONTROL
a	60.5	+12.5	30.8	35	11	-10	29.7	120	99	713.32	676.45	36.87	5	9/9	3/3	0.05	4	225	1850	4160	4400	SOFT	

* — NO LOAD VALUES
** — ON LINE VALUES
HWL — FOREBAY WATER LEVEL
TWL — TAILRACE WATER LEVEL
SNL — SPEED NO LOAD

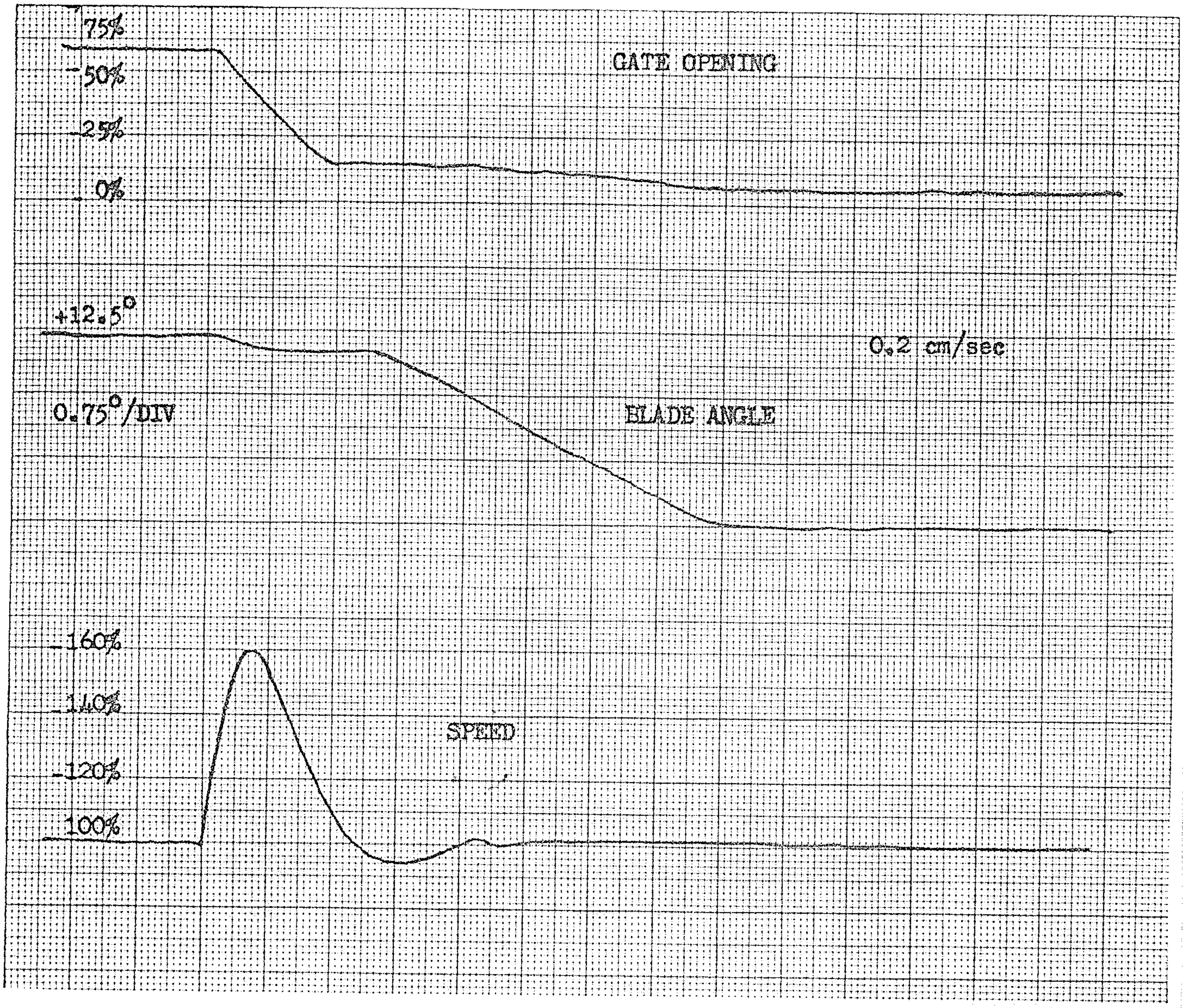


FIGURE E 5 (a)
30.8 MW LOAD REJECTION SOFT SHUTDOWN

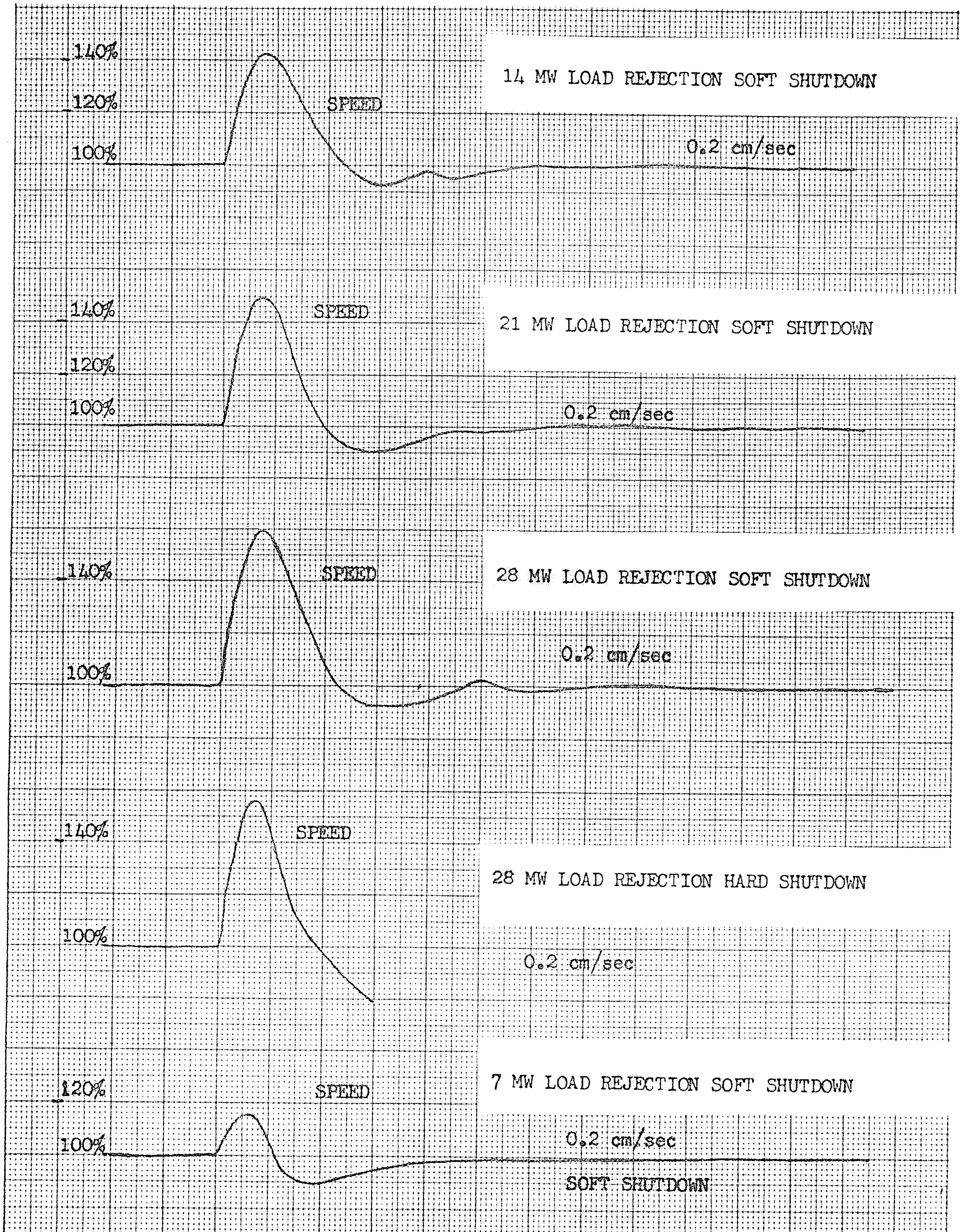


FIGURE E 6 (a)

SPEED TRACES OBTAINED DURING LOAD REJECTION
OF 7, 14, 21, 28 MW SOFT SHUTDOWN AND 28 MW HARD SHUTDOWN

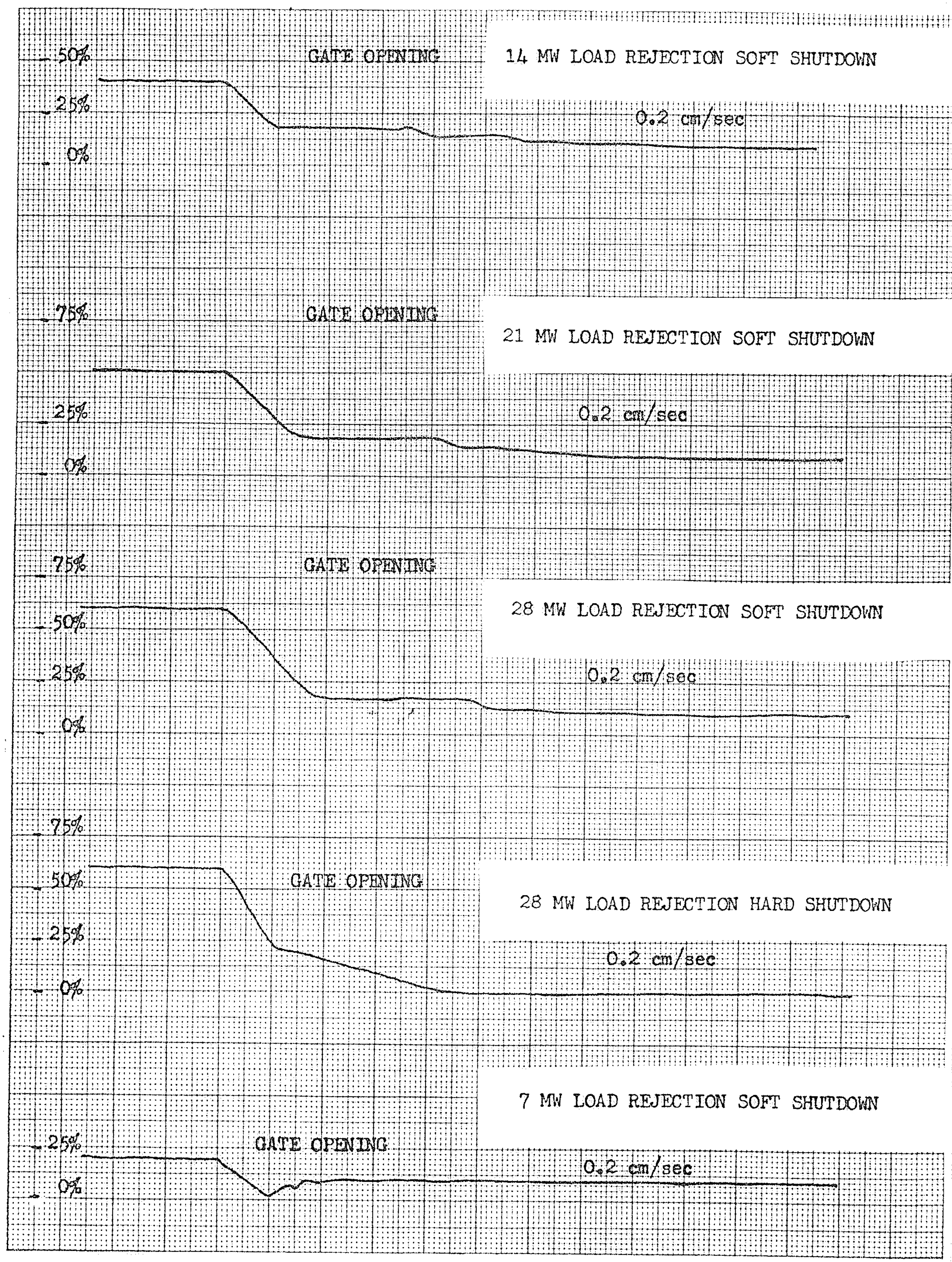


FIGURE E6 (b)

GATE TRACES OBTAINED DURING LOAD REJECTION OF 7, 14, 21 AND 28 MW SOFT SHUTDOWN AND 28 MW HARD SHUTDOWN.

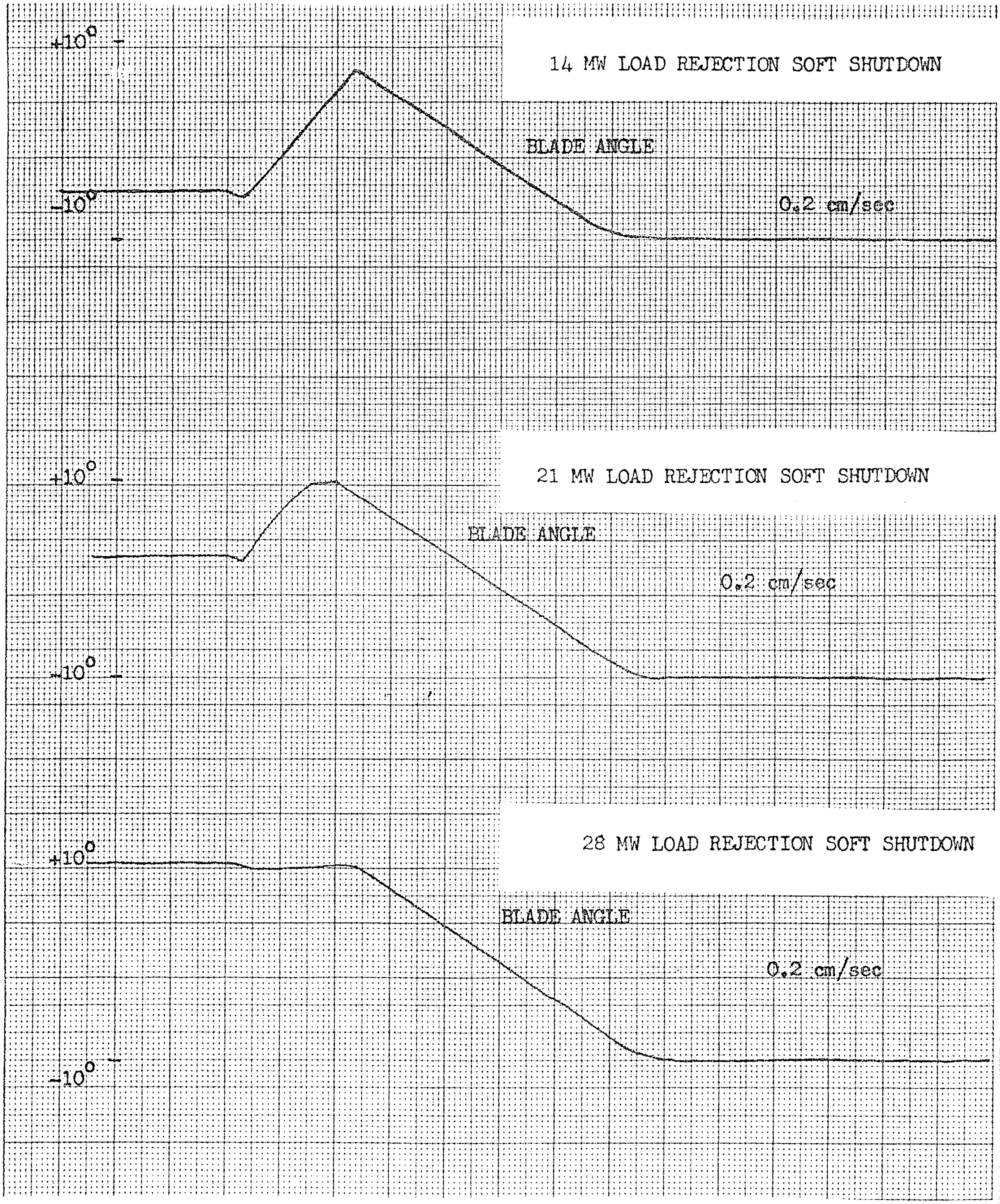


FIGURE E 6 (c)

BLADE ANGLE TRACES OBTAINED DURING LOAD REJECTION
OF 14, 21 AND 28 MW SOFT SHUTDOWN