NACA

RESEARCH MEMORANDUM

for the

Air Materiel Command, U. S. Air Force

CONTROL PERFORMANCE OF GENERAL ELECTRIC FUEL AND TORQUE REGULATOR OPERATING ON T31-3 TURBINE-PROPELLER ENGINE IN SEA-LEVEL TEST STAND

By Frank L. Oppenheimer and James Lazar

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A General Electric fuel and torque regulator was tested in conjunction with a T31-3 turbine-propeller engine in the sea-level static test stand at the NACA Lewis laboratory. The engine and control were operated over the entire speed range: 11,000 rpm, nominal flight idle, to 13,000 rpm, full power. Steady-state and transient data were recorded and are presented with a description of the four control loops being used in the system.

Results of this investigation indicated that single-lever control operation was satisfactory under conditions of test. Transient data presented showed that turbine-outlet temperature did overshoot maximum operating value on acceleration but that the time duration of overshoot did not exceed approximately 1 second. This temperature limiting resulted from a control on fuel flow as a function of engine speed. Speed and torque first reached their desired values 0.4 second from the time of change in power-setting lever position. Maximum speed overshoot was 3 percent.

INTRODUCTION

At the request of the Air Materiel Command, U. S. Air Force, a general program was established at the NACA Lewis laboratory to study several controls operating on a turbine-propeller engine. The present report concerns that part of the program wherein a General Electric fuel and torque regulator, serial No. 1021, was investigated in conjunction with a T31-3 turbine-propeller engine at sea-level static conditions. Representative data for operation of the controlled engine were recorded. These data indicate transient characteristics of the controlled engine for operation in the cruising speed range. This report describes the control, method, and procedure of test, and presents some representative data. The theory of control operation presented in this report is based on literature obtained from the manufacturer, on visual inspection of the control components, and on data obtained from operation of the controlled engine.

DESCRIPTION OF CONTROL

Combined System

The fuel and torque regulator is made up of five components used to control the fuel supply, propeller blade angle, and speed of a gas turbine. These components are:

(1) Torque control loop

(2) Speed governing loop

(3) Manual pressure control system

(4) Altitude compensation loop

(5) Thermal loop (inoperative in the control)

A block diagram of the fuel and torque regulator is shown in figure 1(a). In order to establish operation of the engine at preselected values of controlled variables for a desired power level, a pilot's power-setting lever is incorporated in the regulator. This lever preselects torque Q_s and speed N_s, and puts a safe limit on fuel flow $W_{f,s}$ for a desired condition of engine operation. In this regulator, corrections to engine speed are accomplished primarily by changing fuel flow and corrections to engine torque are accomplished by changing blade angle. Propeller blade angle and fuel valve position are affected by any of the following:

(1) Pilot's power-setting lever

(2) Airframe flight velocity

(3) Governor speed setting

(4) Altitude

The regulator is a hydraulic system, and measurements of all controlled engine variables are converted to hydraulic pressures. The following discussions will deal with each individual loop of the system.

Torque Control Loop

In the torque control loop the propeller blade angle is varied to control the torque absorbed by the propeller. Figure 1(b) is a block diagram of the torque control loop only. The torque error is the absorbed torque of the propeller Q subtracted from a preselected value of torque Q_s set by the power-setting lever HP_s. This error Q_s-Q causes an unbalance of pressures in the control loop and is eliminated by the repositioning of the blade-angle input lever β_a with an integral torque error correction represented by the function K_1/p. The positioning of the blade-angle input lever β_a linearly schedules blade angle β by means of a hydraulic blade-angle-change mechanism represented by the function $\frac{K_2}{1 + \tau_s p}$. With fuel flow held constant, changes in propeller blade angle result in a torque change $\left(\frac{\Delta Q}{\Delta \beta}\right)_{W_f}$ and also cause a speed change $\left(\frac{\Delta N}{\Delta \beta}\right)_{W_f}$.

Speed Control Loop

In the speed control loop fuel flow is primarily varied to control speed. A block diagram of the speed control loop is shown in figure 1(c). Engine turbine speed N is sensed by a governor. The speed error is the actual engine operating speed subtracted from a preselected value of engine speed N_s set by the power-setting lever. If speed increases beyond the desired value, the error N_s-N is eliminated by reduction of variable-control oil pressure (VCO) with a speed error correction represented by the function $F_1(p)$. A reduction in variable-control oil pressure causes the fuel pump to reduce fuel flow W_f in a manner represented by the function $F_2(p)$. A reduction in fuel flow with blade angle held constant causes speed to reduce as given by the response $\left(\frac{\Delta N}{\Delta W_f}\right)_\beta$. Torque also changes with a change in fuel flow $\left(\frac{\Delta Q}{\Delta W_f}\right)_\beta$ if blade angle is held constant. Fuel flow is limited to approximately 10 percent over that required for the preselected speed. This means of restricting fuel flow is indicated in figure 1(a) as the fuel-flow limiter.

If engine speed drops below the limiting value of speed reset, a torque reset lever is actuated to reduce blade angle, thereby reducing torque and increasing speed to a value such that the speed error is small enough to be corrected by fuel flow.

Manual Pressure Control System

The manual pressure control operates in the starting regime only. The airframe cannot be controlled in flight with this system. The manual control varies fuel flow with blade angle held constant from ground idle operation at 8000 rpm to flight idle engine speed of 11,000 rpm. The automatic control loops function when the engine is operating in the cruising speed range 11,000 to 13,000 rpm. In the manual pressure control system variable-control oil pressure is preselected for a desired turbine speed. A block diagram of the manual pressure control system is shown in figure 1(d).

A change in position of the power-setting lever HP_s manually changes variable-control oil pressure VCO. An increase or decrease in variable-control oil pressure increases or decreases fuel flow W_f in a manner represented by the function $F_2(p)$. Thus, speed increases with fuel flow and, with blade angle held constant, torque is changed when fuel flow is varied, as given by the response $\left(\frac{\Delta Q}{\Delta W_f}\right)_\beta$.

Altitude Compensation Loop

Altitude compensation is utilized to maintain the turbine at a safe operating temperature. When operating at altitude, the fuel flow required is less than at sea level because the mass flow of air is reduced. In the altitude compensation loop a variable ratio device is used to reduce available fuel flow to the combustor with altitude and to decrease the amount of governor overspeed correction. Figure 1(e) is a block diagram of the altitude compensation loop. The system consists of two bellows opposing each other, one actuated by compressor inlet pressure CIP, and the other sealed at atmospheric pressure. The action of these bellows changes variable-control oil pressure to speed error gain in order to meet altitude requirements. This action is represented by the function K_3. In this control loop variable-control oil pressure changes with respect to speed error in a manner represented by the function $F_1(p)$ modified by the function K_3. Fuel flow changes with a change in variable-control oil pressure as represented by the function $F_2(p)$.

APPARATUS

Engine Installation

Engine. - T31-3 turbine-propeller engine, serial No. GE-021-014

Propeller. - Aeroproducts, A542-F-17

Control. - General Electric fuel and torque regulator, serial No. 1021, compensated for altitude

Test facilities. - NACA Lewis laboratory sea-level static test stand

Instrumentation

Recorder. - Transient responses of engine parameters were recorded on a multiple channel, galvanometer type, photorecording oscillograph with 40-cycles-per-second natural-frequency galvanometer elements damped at 0.8 damping ratio. A time scale was recorded on the lower edge of the oscillograph chart, one pip for each tenth of a second.

Parameters recorded. - Table I lists the measured quantity, steady-state instrumentation, and transient instrumentation for the following parameters:

Engine speed

Power-setting lever position

Fuel flow, proportional to static pressure

Torque

Turbine-outlet temperature

Blade-angle input

Blade angle

In the basic fuel loop, the variable-control oil pressure was recorded only under steady-state conditions.

PROCEDURE

Transient operation of the controlled engine was obtained by manually advancing or cutting back the power-setting lever in a stepwise manner. Engine parameters were measured continuously on a photorecording oscillograph. Before and after each transient, photographs of steady-state values indicated on panel meters were taken to calibrate the individual oscillograph traces.

Decreasing and increasing step changes in the power-setting lever position were made according to the following speed and power settings at sea-level, static conditions:

Maximum power - 11,000 rpm
13,000 - 11,000 rpm
12,500 - 11,000 rpm
12,000 - 11,000 rpm
11,500 - 11,000 rpm

Maximum power - 12,000 rpm
13,000 - 12,000 rpm
12,500 - 12,000 rpm

Maximum power - 12,500 rpm
13,000 - 12,500 rpm

Maximum power - 13,000 rpm

Steady-state readings were taken of speed, fuel flow, torque, and temperature in order to obtain a schedule of these parameters at various power-setting lever positions from idle at 22° to maximum power at 65°.

SCHEDULING OF PARAMETERS

The control regulates fuel flow to the engine by means of a variable displacement fuel pump (reference 1). The displacement, and thus the output, of the pump is determined by a pilot valve actuated by variable-control oil pressure supplied by the torque regulator. Figure 2(a) is a curve of fuel flow variation with variable-control oil pressure, as determined from steady-state operation of the torque regulator at various power lever settings. In steady-state operation fuel flow varies linearly with variable-control oil pressure. Under transient conditions the fuel pump approximates a first-order lag system (reference 1).

The magnitudes of speed, fuel flow, torque, and temperature during engine operation are determined by efficiency, safety, and time response. By means of scheduling the aforementioned parameters for each power-setting lever position, efficient matching of torque and speed, safe temperature limits, and sufficiently large gains for rapid response can be established. Figure 2(b) is the schedule of steady-state variation of speed, fuel flow, blade angle, torque, and temperature with power-setting lever position for the fuel and torque regulator.

EVALUATION OF CONTROL BEHAVIOR

Control Fulfillment of Accepted Criteria

Four general turbine-propeller engine control requirements are as follows:

(1) Adaptability to a large number of different turbine-propeller engines

(2) Ability to prevent the engine from being damaged

(3) Operation without attention from the pilot except to change called-for thrust

(4) Response of the engine in the length of time and manner desired

From the transient data presented in figure 3 and indexed in table II, this fuel and torque regulator control can be said to meet several of the aforementioned requirements. It can be utilized to control turbine-propeller engines where torque can be directly measured and where propeller blade angle is a linear function of the input to the blade angle controller.

The control is designed to correct blade angle in order to eliminate any torque error. Therefore, (1) torque has to be known at any instant, and (2) blade angle has to respond in a linear fashion to any blade-angle input called for in order to enable the engine to correct quickly and consistently to the conditions called for.

The control has incorporated within it a limit to prevent fuel flow from exceeding by more than approximately 10 percent the amount required for the preselected engine speed. This provision serves to prevent the engine from exceeding a maximum safe turbine-outlet operating temperature of 1265° F for more than approximately 1 second at any level of engine operation, as indicated by all data obtained in this investigation. Extended operation above the aforementioned temperature could cause severe damage to the engine turbine. These data also indicate that for the conditions existing during this investigation temperature is a function of fuel flow and is kept at a safe level by the limiting of fuel flow as a function of speed.

This control requires no attention from the pilot except to change the power setting.

For an increase in power from any value of speed above 11,500 rpm to maximum speed and power, the control is able to correct engine parameters without speed, blade-angle, or engine-torque dips at the start of the called-for change in these parameters, as indicated by the data. If increases in power are called for from values of speed below 11,500 rpm, blade-angle dips do occur at the start of the called-for change in parameters, either for a small incremental change in power or for a burst to full power, as shown in figures 3(a) concluded, 3(b) concluded, 3(c) concluded, and 3(e) concluded. Although a direct measurement of engine thrust was not obtained in this investigation, the aforementioned dips in blade angle possibly could have produced a dip in propeller torque great enough to more than offset the effect of increasing speed, thus causing a resultant thrust dip.

From compilation of all data obtained in this investigation, the maximum rise time for first reaching the desired value in speed and torque is 0.4 second from the time of change in power-setting lever position. This time response is quite satisfactory, considering the fact that the response time of an airframe is many times the aforementioned rise time.

Specific Control Characteristics

For a decreasing power change, the controlled engine parameters tend to oscillate two or three times after the desired value has been reached. When an increase in power is called for, the parameters oscillate once or twice before steadying out. For a given increment in the power range of the engine, the amplitudes of oscillation of parameters are larger for a decrease in power than for an increase in power. Although blade angle changes are never abrupt, fuel flow tends to overshoot when a decrease in power is called for, whereas for an increase in power the fuel-flow limiter attenuates the amplitude of oscillation considerably. This tendency towards greater instability for decreases in power holds throughout the engine cruising speed range, regardless of the size of the incremental power change, as indicated by the data.

In general, torque approaches its final value with one fairly large overshoot and has one or more small oscillations following the initial rise. Speed has a moderate overshoot, dip, and then it settles out. From compilation of data obtained in this investigation, the maximum speed overshoot of its rated value is 3 percent. Temperature overshoots and oscillates at large amplitudes for decreases in power. It overshoots and oscillates more moderately for increases in power. Thus the large overshoot of fuel flow for decreases in power causes similar behavior in temperature. Therefore, after consideration of the behavior of all the engine parameters, an improvement in response to decreasing power commands might be had by adding a variable minimum fuel-flow limiter. This addition could establish more stable performance by reducing the amplitude of oscillations due to fuel flow variation.

From a review of the control system, an increase in speed above the desired value is corrected by a decrease in fuel flow. Therefore, engine speed can be reduced if a failure of the hydraulic propeller mechanism causes the propeller to go to flat pitch; however, no provision has been made to reduce fuel flow in case the propeller fails and goes to full pitch. There is an indication that the addition of an interconnection between torque and fuel flow could provide safe control of the engine if the hydraulic propeller mechanism fails and the propeller goes to full pitch.

SUMMARY OF RESULTS

The following results were obtained from a sea-level static investigation of a General Electric fuel and torque regulator on a T31-3 turbine-propeller engine at the NACA Lewis laboratory:

1. Single-lever operation with this control was satisfactory.

2. Duration of temperature overshoot beyond the safe turbine-outlet operating temperature of 1265° F did not exceed approximately 1 second at any level of engine operation.

3. Temperature limiting resulted from a control on fuel flow as a function of engine speed.

4. The maximum rise time for first reaching the desired value in speed and torque was 0.4 second from the time of change in power-setting lever position.

5. Maximum speed overshoot was 3 percent.

Possibly the addition of a variable minimum fuel-flow limiter for decreasing power commands could establish more stable performance by reducing the amplitudes of oscillations due to fuel flow variation.

There is an indication that the addition of an interconnection between torque and fuel flow could provide safe control of the engine if the hydraulic propeller mechanism fails and the propeller goes to full pitch.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 12, 1951

APPENDIX - SYMBOLS

The following symbols are used in this report:

CIP	compressor-inlet pressure
$F_1(p)$	function representing speed error correction
$F_2(p)$	function representing fuel pump operation
HP_s	power-setting lever
K_1	torque error correction gain
K_2	blade angle to input gain
K_3	variable-control oil pressure to speed error gain
N	turbine operating speed, rpm
N_s	preselected turbine operating speed, rpm
p	differential operator, $\frac{d}{dt}$
Q	absorbed torque of the propeller
Q_s	preselected propeller torque
S	power-setting lever position
T	temperature
VCO	variable-control oil pressure
W_f	fuel flow
$W_{f,s}$	preselected fuel flow
β	blade angle, deg
β_a	blade-angle input lever
Δ	incremental change
τ_s	hydraulic blade-angle-change mechanism time constant

Subscripts:

i	initial
f	final

REFERENCE

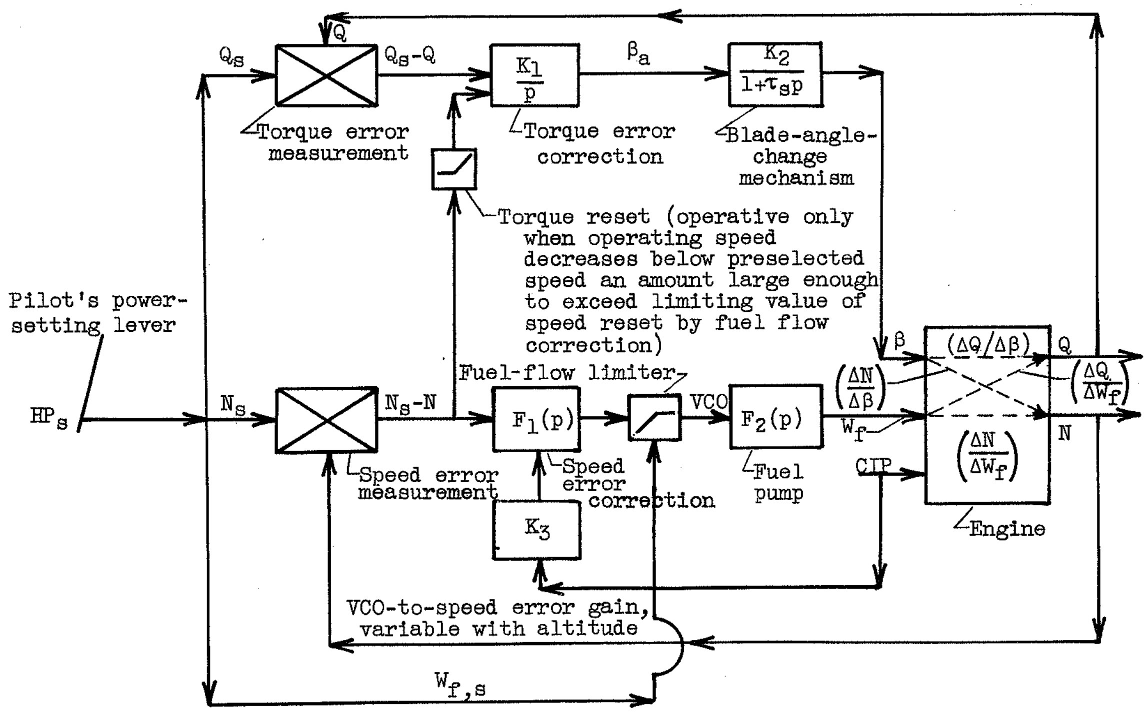
1. Shames, Harold, Himmel, Seymour C., and Blivas, Darnold: Frequency Response of Positive-Displacement Variable-Stroke Fuel Pump. NACA TN 2109, 1950.

TABLE I - INSTRUMENTATION

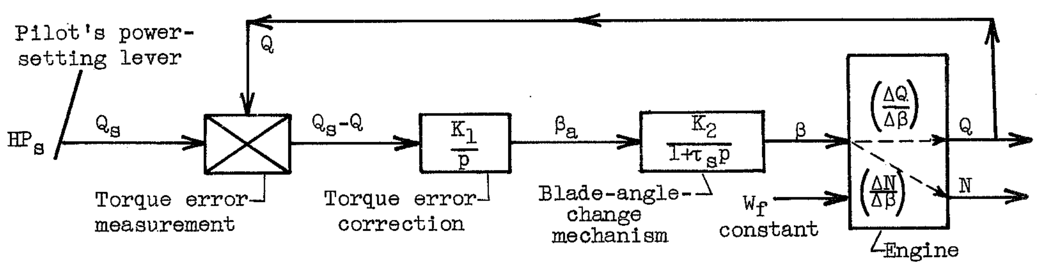
Measured quantity	Steady-state instrumentation	Transient instrumentation	
		Sensor	Frequency response range (cps)
Engine speed	Three-phase tachometer generator	Direct-current generator	Limited by filter circuit 0-2.65
Power lever position	Wire-wound potentiometer connected to give position indication on microammeter	Wire-wound potentiometer connected to give position indication on oscillograph	40 cps natural frequency, 0.8 damping ratio
Fuel flow, proportional to static pressure	Rotameter	Aneroid-type pressure sensor with strain-gage element	40 cps natural frequency, 0.8 damping ratio
Torque	Bourdon-type gage	Aneroid-type pressure sensor with strain-gage element	40 cps natural frequency, 0.8 damping ratio
Turbine-outlet temperature	One-chromel-alumel thermocouple connected to Brown recorder	Three 24-gage chromel constantan thermocouples in series	0-1
Blade angle input	Wire-wound potentiometer connected to give position indication on microammeter	Wire-wound potentiometer connected to give position indication on oscillograph	40 cps natural frequency, 0.8 damping ratio
Blade angle	Wire-wound potentiometer connected to give position indication on microammeter	Wire-wound potentiometer connected to give position indication on oscillograph	40 cps natural frequency, 0.8 damping ratio
Variable-control oil pressure	Bourdon-type gage		

TABLE II - INDEX TO TRANSIENT RUNS

Figure	Throttle position, (deg)	
	Initial	Final
3(a)	64.5	41.0
3(a) concluded	41.5	64.5
3(b)	53.3	41.0
3(b) concluded	41.0	53.3
3(c)	46.8	41.0
3(c) concluded	41.0	46.8
3(d)	44.5	40.5
3(d) concluded	41.0	44.5
3(e)	42.7	41.0
3(e) concluded	41.0	42.7
3(f)	63.8	44.5
3(f) concluded	44.5	63.5
3(g)	53.3	44.5
3(g) concluded	44.5	53.8
3(h)	47.0	44.5
3(h) concluded	44.5	47.0
3(i)	64.5	47.0
3(i) concluded	47.0	64.2
3(j)	53.3	47.0
3(j) concluded	47.0	53.0
3(k)	65.0	53.3
3(k) concluded	53.3	64.5

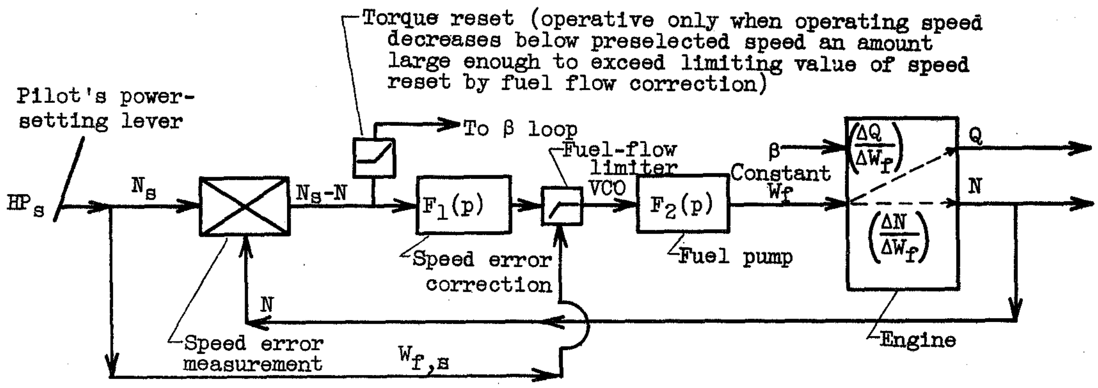


(a) Combined system.

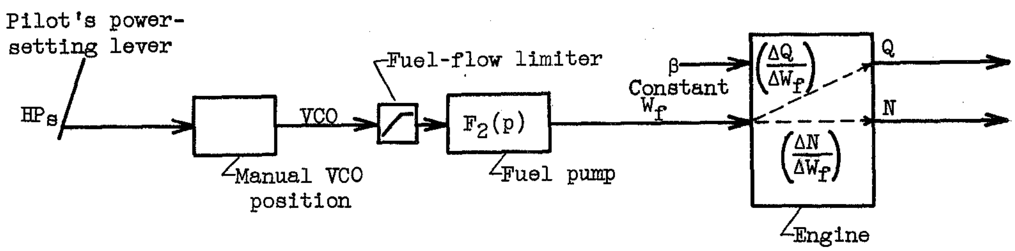


(b) Torque control loop.

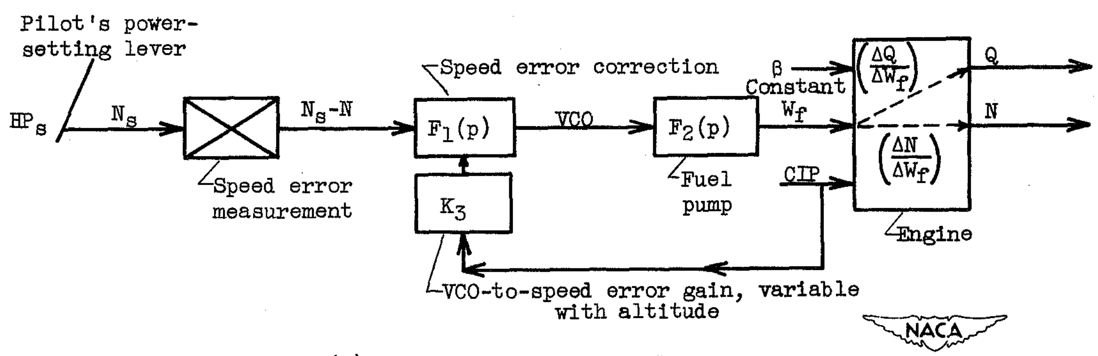
Figure 1. - Block diagram of fuel and torque regulator.



(c) Speed control loop.

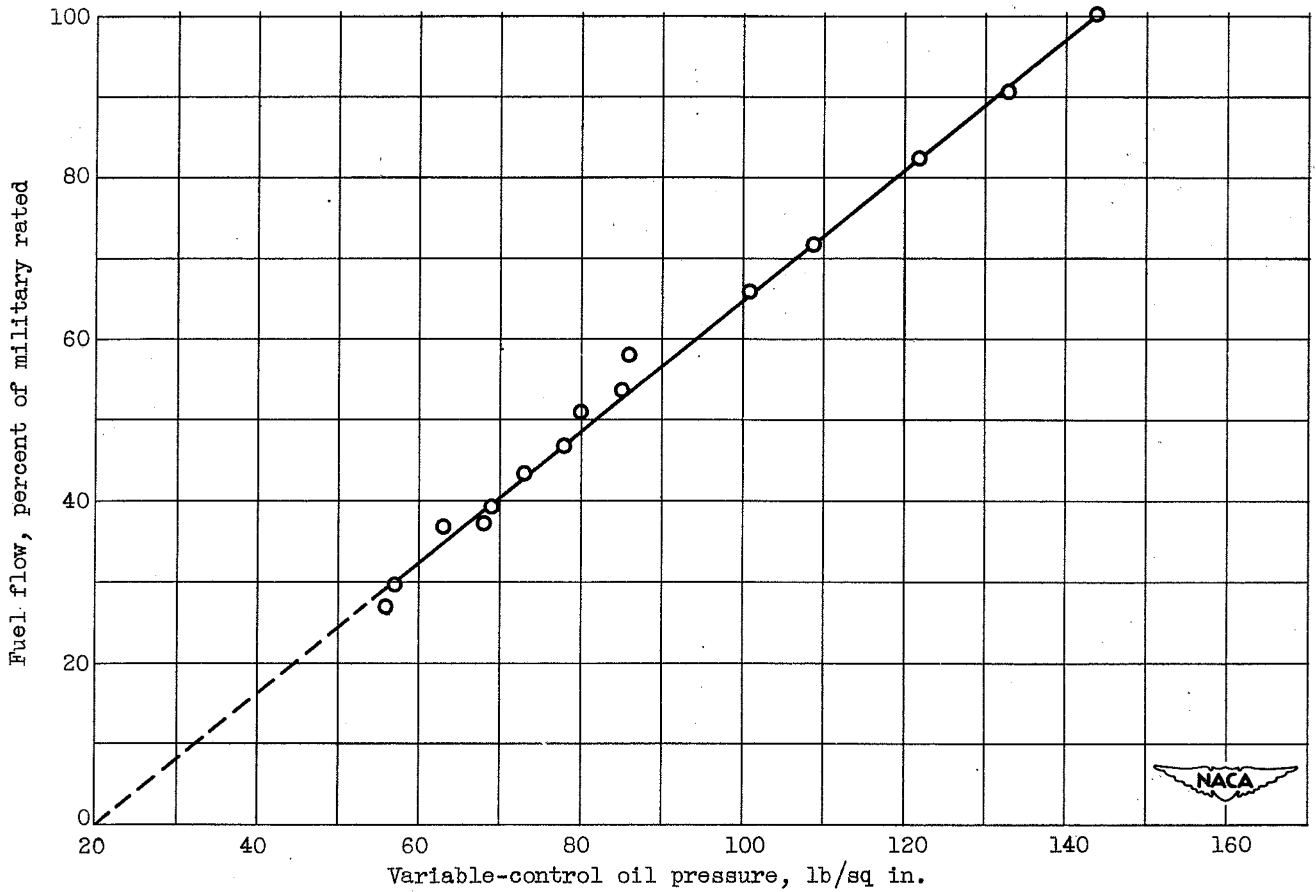


(d) Manual pressure control system.



(e) Altitude compensation loop.

Figure 1. - Concluded. Block diagram of fuel and torque regulator.



(a) Variation of fuel flow with variable-control oil pressure; steady state.

Figure 2. - Parameter schedules.

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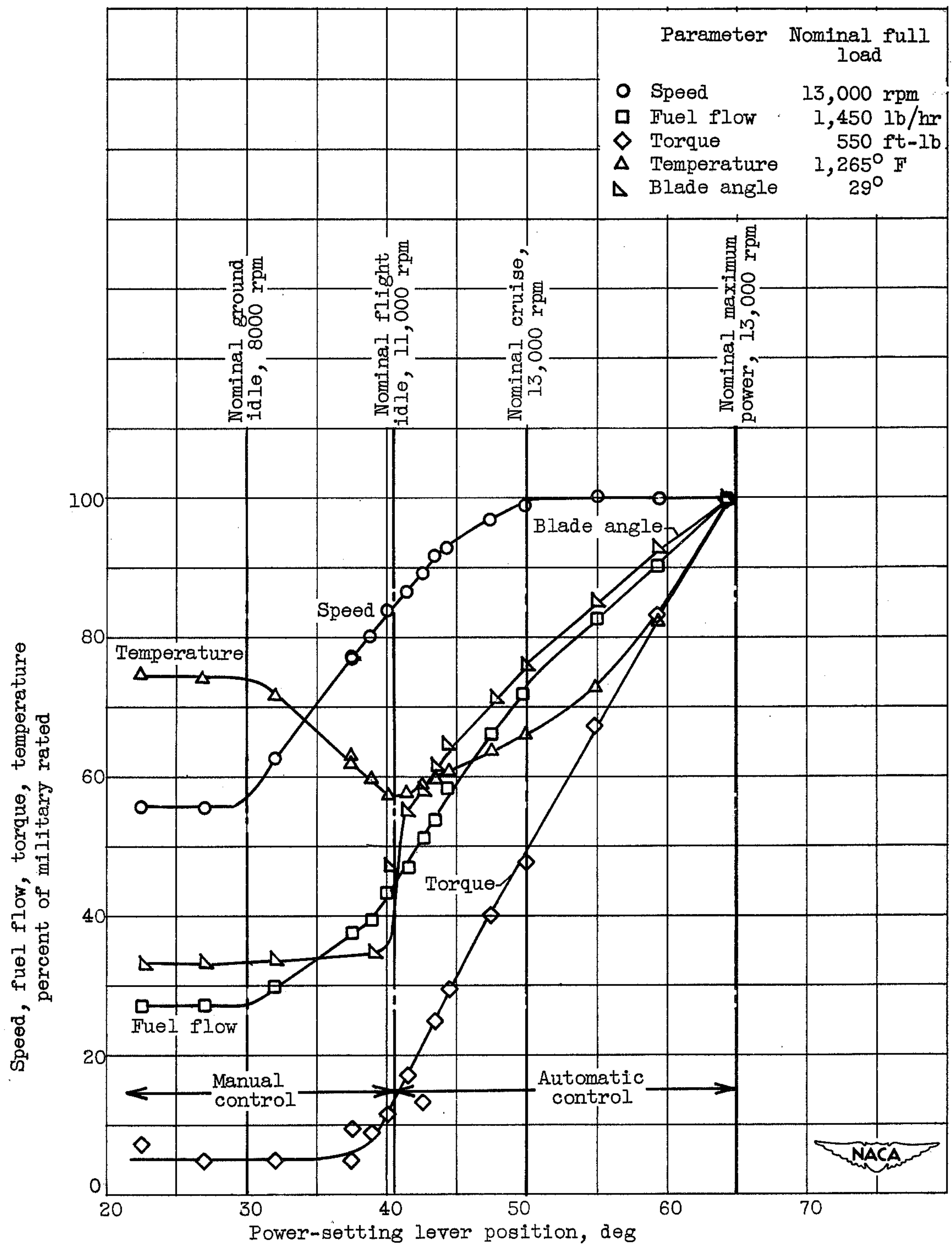

(b) Steady-state variation of speed, fuel flow, torque, and temperature with power-setting lever position.

Figure 2. - Concluded. Parameter schedules.

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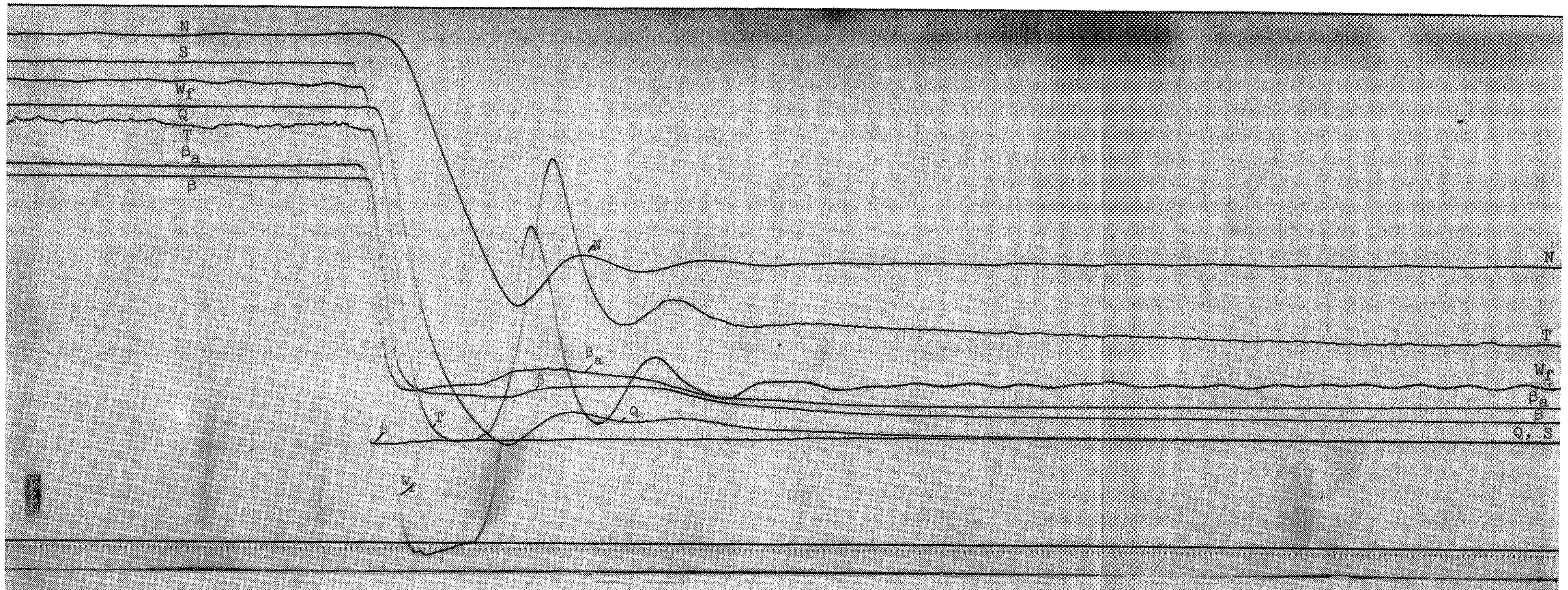
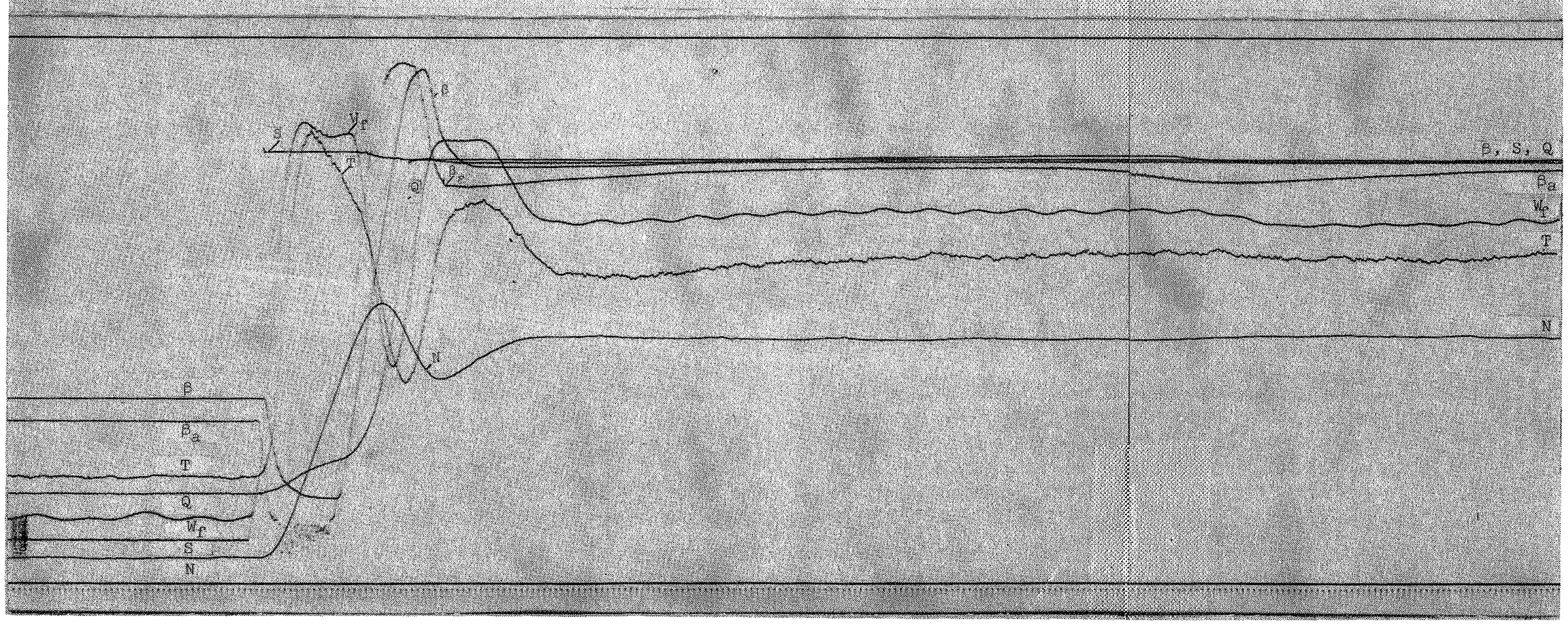


N_i, 13,372 rpm
S_i, 64.5°
$W_{f,i}$, 1497 lb/hr
Q_i, 571.7 ft-lb
T_i, 1247° F
$\beta_{a,i}$, 52 μa
β_i, 28.6°

N_f, 11,470 rpm
S_f, 41.0°
$W_{f,f}$, 678.1 lb/hr
Q_f, 114.5 ft-lb
T_f, 779.5° F
$\beta_{a,f}$, 23 μa
β_f, 15.0°

(a) Throttle position, 64.5° to 41.0°.



N_i, 11,481 rpm
S_i, 41.5°
$W_{f,i}$, 687.5 lb/hr
Q_i, 98.74 ft-lb
T_i, 756.0° F
$\beta_{a,i}$, 24 μa
β_i, 15.0°

N_f, 13,382 rpm
S_f, 64.5°
$W_{f,f}$, 1493 lb/hr
Q_f, 568.7 ft-lb
T_f, 1211° F
$\beta_{a,f}$, 52 μa
β_f, 28.6°

(a) Concluded. Throttle position, 41.5° to 64.5°.

Figure 3. - Transient operation of automatically controlled engine

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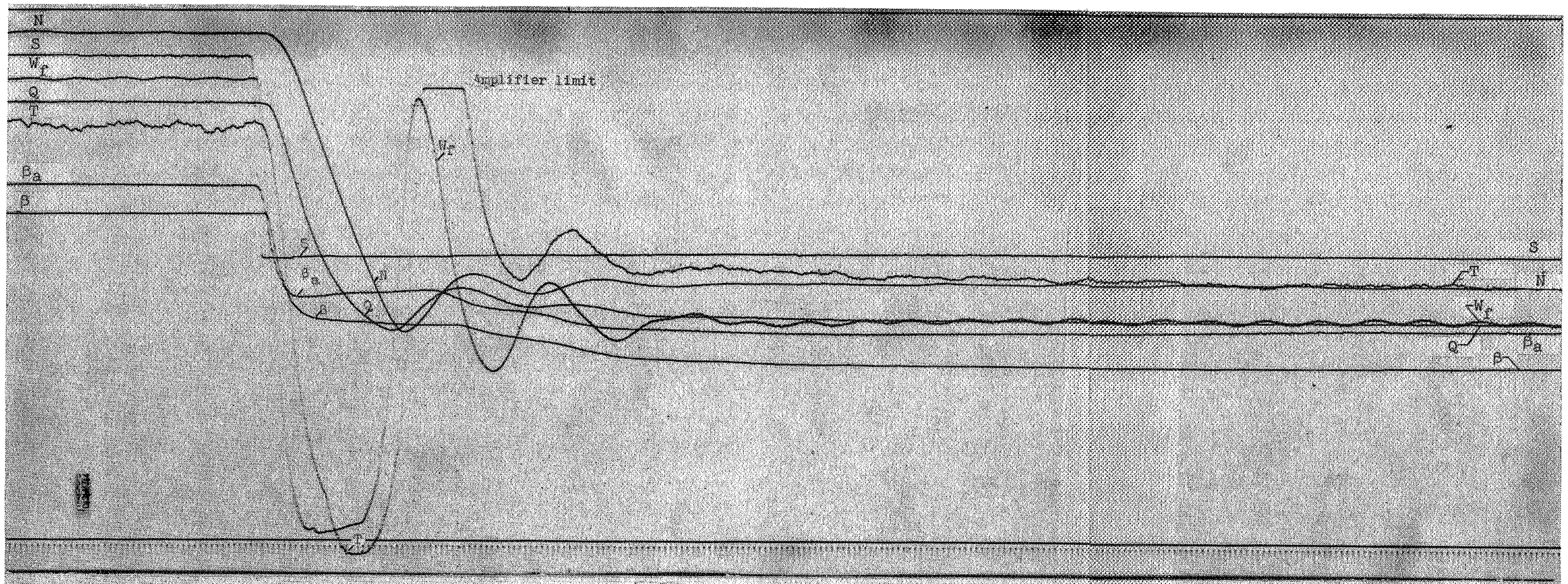
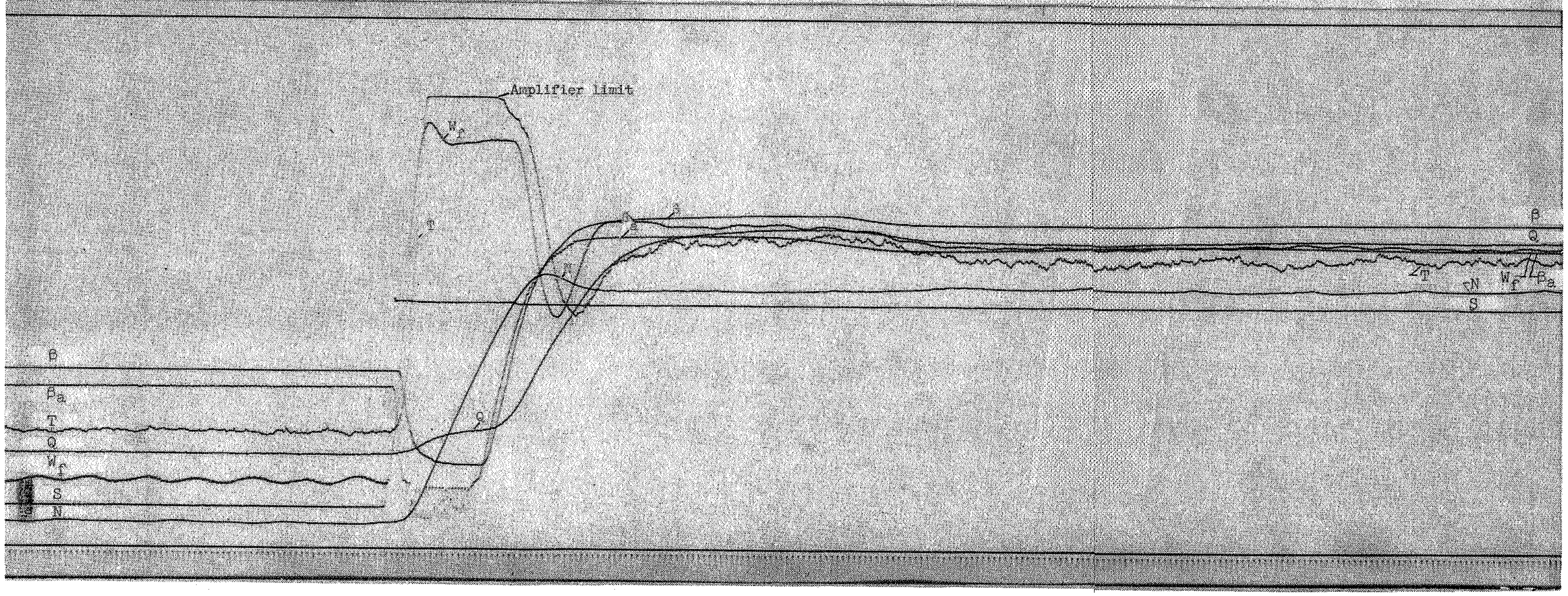


N_i, 13,496 rpm
S_i, 53.3°
$W_{f,i}$, 1182 lb/hr
Q_i, 355.5 ft-lb
T_i, 899.1° F
$\beta_{a,i}$, 41 μa
β_i, 23.4°

N_f, 11,367 rpm
S_f, 41.0°
$W_{f,f}$, 664.6 lb/hr
Q_f, 110.6 ft-lb
T_f, 753.9° F
$\beta_{a,f}$, 24 μa
β_f, 14.8°

(b) Throttle position, 53.3° to 41.0°.



N_i, 11,393 rpm
S_i, 41.0°
$W_{f,i}$, 664.6 lb/hr
Q_i, 94.79 ft-lb
T_i, 744.3° F
$\beta_{a,i}$, 24 μa
β_i, 14.8°

N_f, 13,496 rpm
S_f, 53.3°
$W_{f,f}$, 1190 lb/hr
Q_f, 339.7 ft-lb
T_f, 899.1° F
$\beta_{a,f}$, 42 μa
β_f, 23.6°

(b) Concluded. Throttle position, 41.0° to 53.3°.

Figure 3. - Continued. Transient operation of automatically controll engine.

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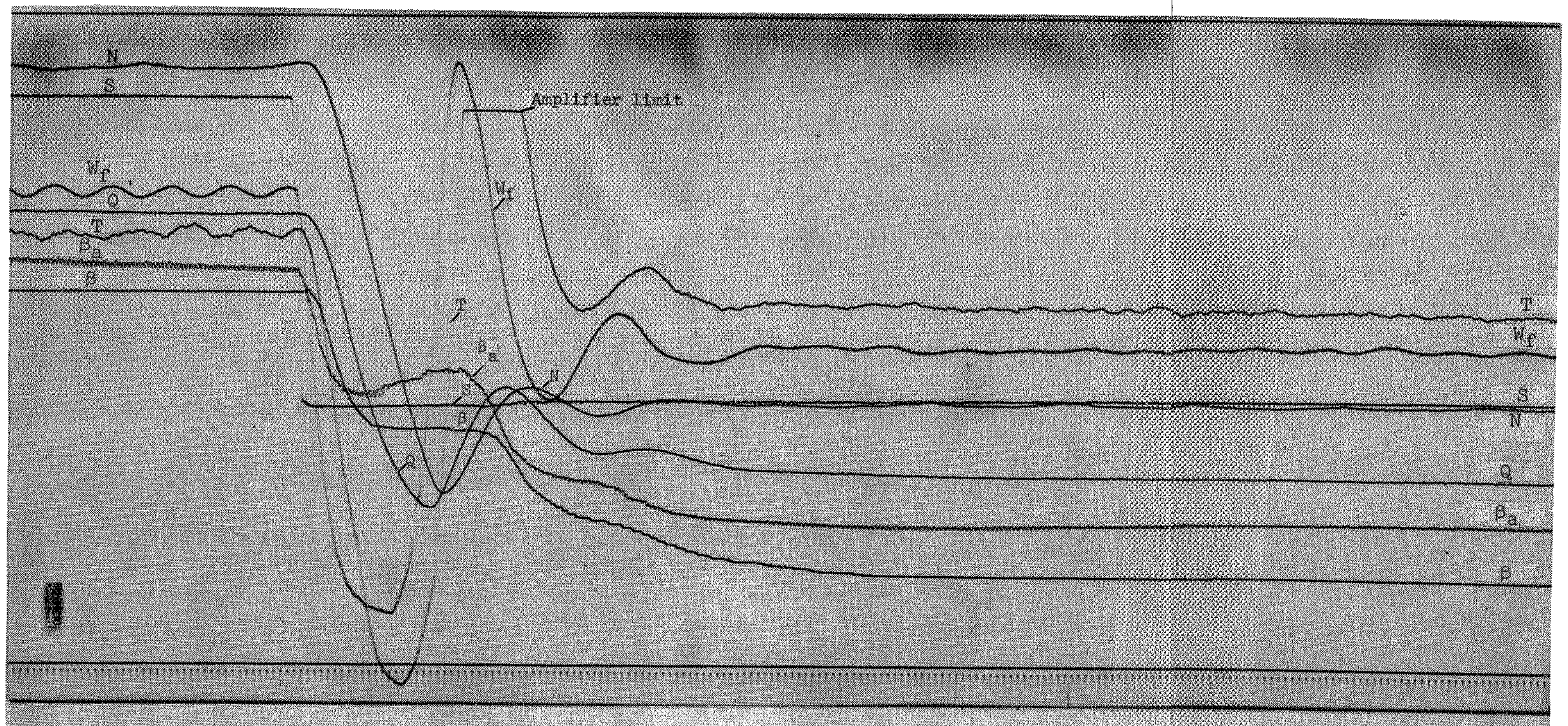
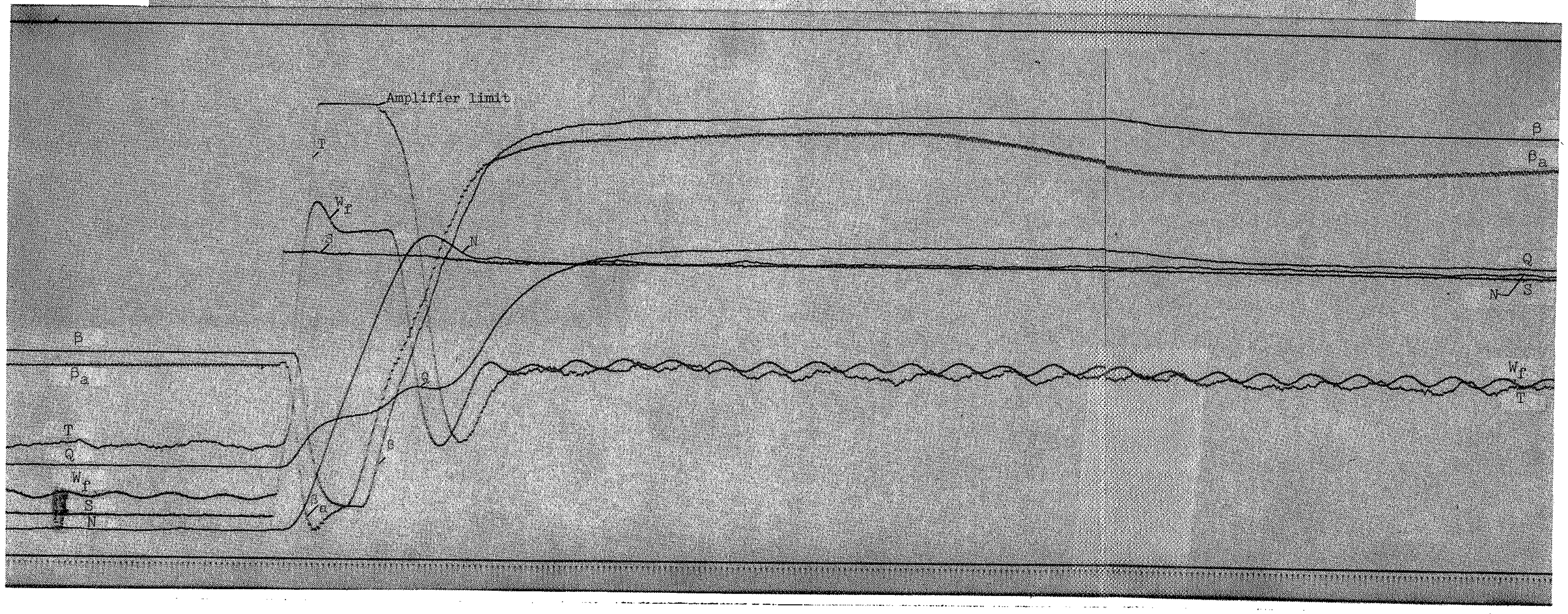


N_i, 12,891 rpm
S_i, 46.8°
$W_{f,i}$, 951.1 lb/hr
Q_i, 216.2 ft-lb
T_i, 820.1° F
$\beta_{a,i}$, 34 μa
β_i, 20.0°

N_f, 11,357 rpm
S_f, 41.0°
$W_{f,f}$, 664.6 lb/hr
Q_f, 111.6 ft-lb
T_f, 752.8° F
$\beta_{a,f}$, 24 μa
β_f, 15.0°

(c) Throttle position, 46.8° to 41.0°.



N_i, 11,341 rpm
S_i, 41.0°
$W_{f,i}$, 664.6 lb/hr
Q_i, 96.76 ft-lb
T_i, 742.1° F
$\beta_{a,i}$, 24 μa
β_i, 15.0°

N_f, 12,907 rpm
S_f, 46.8°
$W_{f,f}$, 958.4 lb/hr
Q_f, 193.5 ft-lb
T_f, 816.9° F
$\beta_{a,f}$, 34 μa
β_f, 20.0°

(c) Concluded. Throttle position, 41.0° to 46.8°.

Figure 3. - Continued. Transient operation of automatically controllengine.

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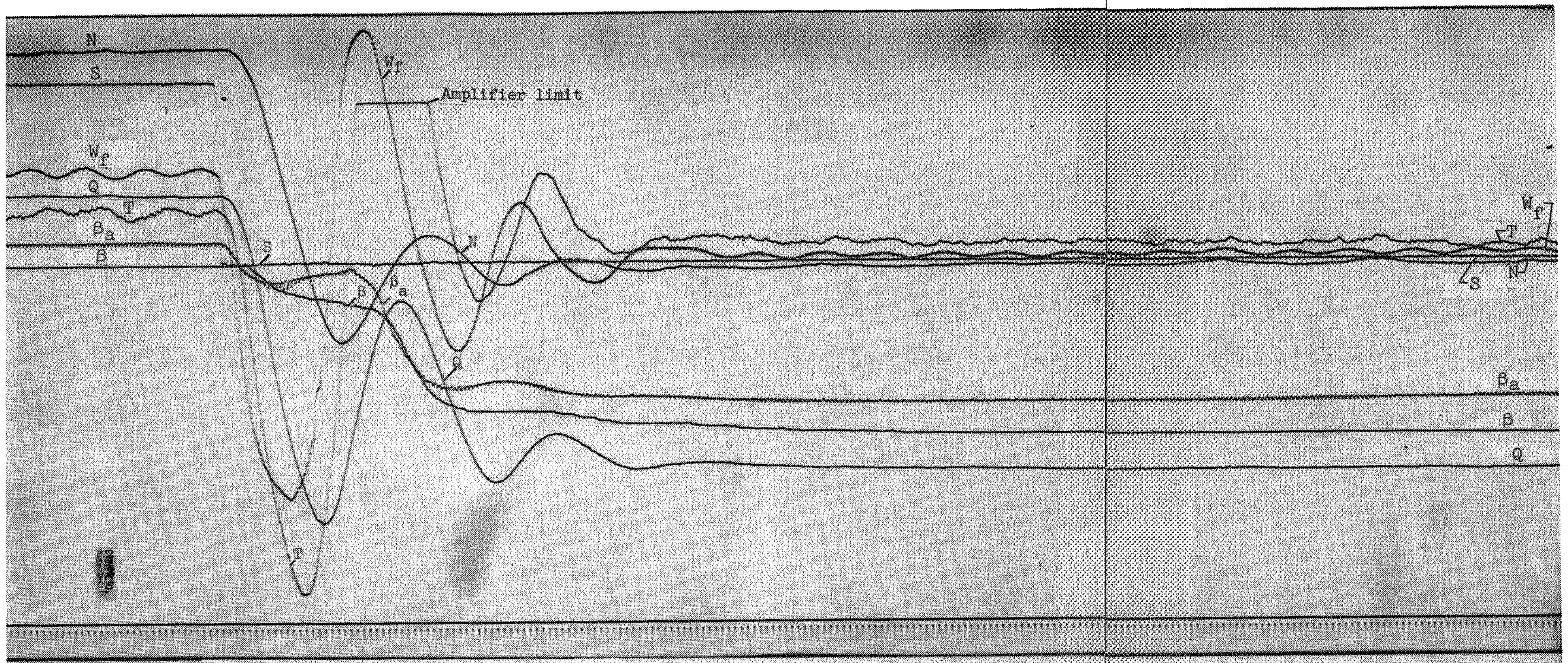
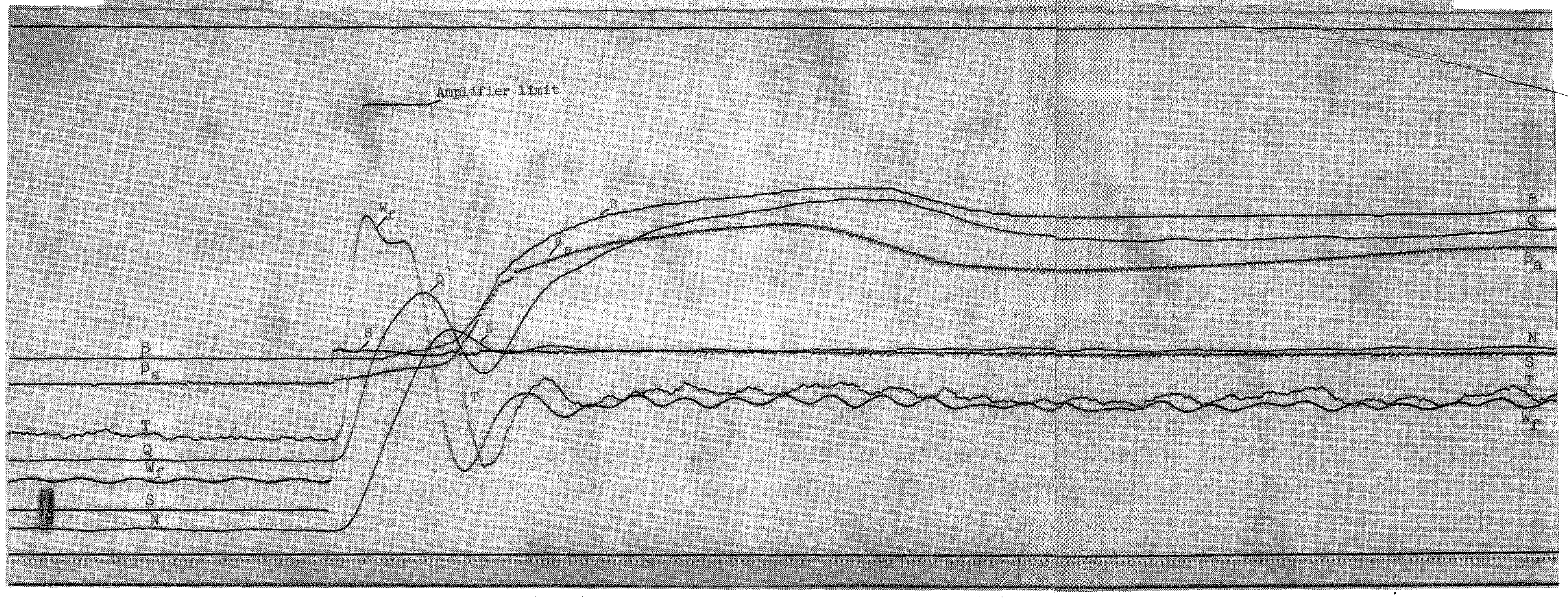


N_i, 12,390 rpm
S_i, 44.5°
$W_{f,i}$, 845.9 lb/hr
Q_i, 163.9 ft-lb
T_i, 791.2° F
$\beta_{a,i}$, 30 μa
β_i, 18.4°

N_f, 11,315 rpm
S_f, 40.5°
$W_{f,f}$, 662.5 lb/hr
Q_f, 106.6 ft-lb
T_f, 751.7° F
$\beta_{a,f}$, 24 μa
β_f, 15.15°

(d) Throttle position, 44.5° to 40.5°.



N_i, 11,357 rpm
S_i, 41.0°
$W_{f,i}$, 664.6 lb/hr
Q_i, 95.78 ft-lb
T_i, 744.3° F
$\beta_{a,i}$, 24 μa
β_i, 15.25°

N_f, 12,390 rpm
S_f, 44.5°
$W_{f,f}$, 842.7 lb/hr
Q_f, 156.0 ft-lb
T_f, 784.8° F
$\beta_{a,f}$, 30 μa
β_f, 18.2°

(d) Concluded. Throttle position, 41.0° to 44.5°

Figure 3. - Continued. Transient operation of automatically conrolled engine.

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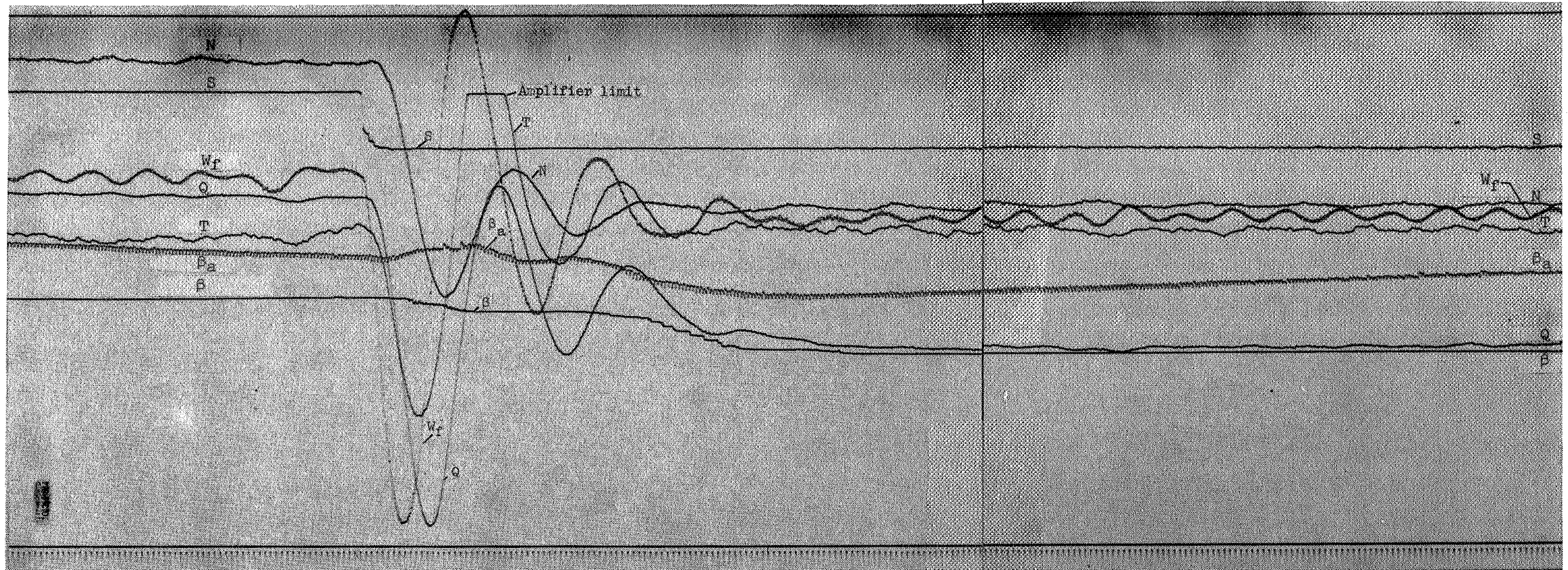
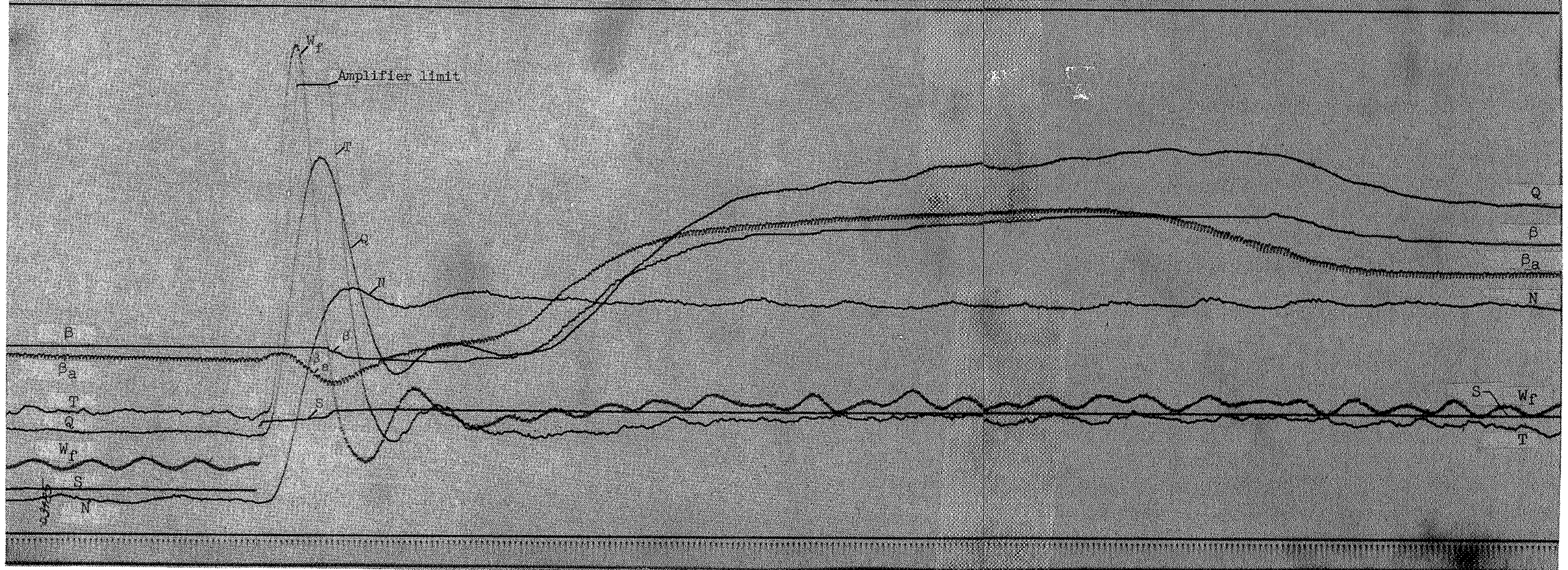


N_i, 11,873 rpm
S_i, 42.7°
$W_{f,i}$, 746.9 lb/hr
Q_i, 123.4 ft-lb
T_i, 763.5° F
$\beta_{a,i}$, 26 μa
β_i, 16.6°

N_f, 11,470 rpm
S_f, 41.0°
$W_{f,f}$, 690.6 lb/hr
Q_f, 110.6 ft-lb
T_f, 753.9° F
$\beta_{a,f}$, 26 μa
β_f, 16.05°

(e) Throttle position, 42.7° to 41.0°.



N_i, 11,357 rpm
S_i, 41.0°
$W_{f,i}$, 669.8 lb/hr
Q_i, 98.74 ft-lb
T_i, 747.5° F
$\beta_{a,i}$, 25 μa
β_i, 15.6°

N_f, 11,894 rpm
S_f, 42.7°
$W_{f,f}$, 753.1 lb/hr
Q_f, 122.4 ft-lb
T_f, 766.7° F
$\beta_{a,f}$, 26 μa
β_f, 16.85°

(e) Concluded. Throttle position, 41.0° to 2.7°.

Figure 3. - Continued. **Transient operation of automatical controlled engine.**

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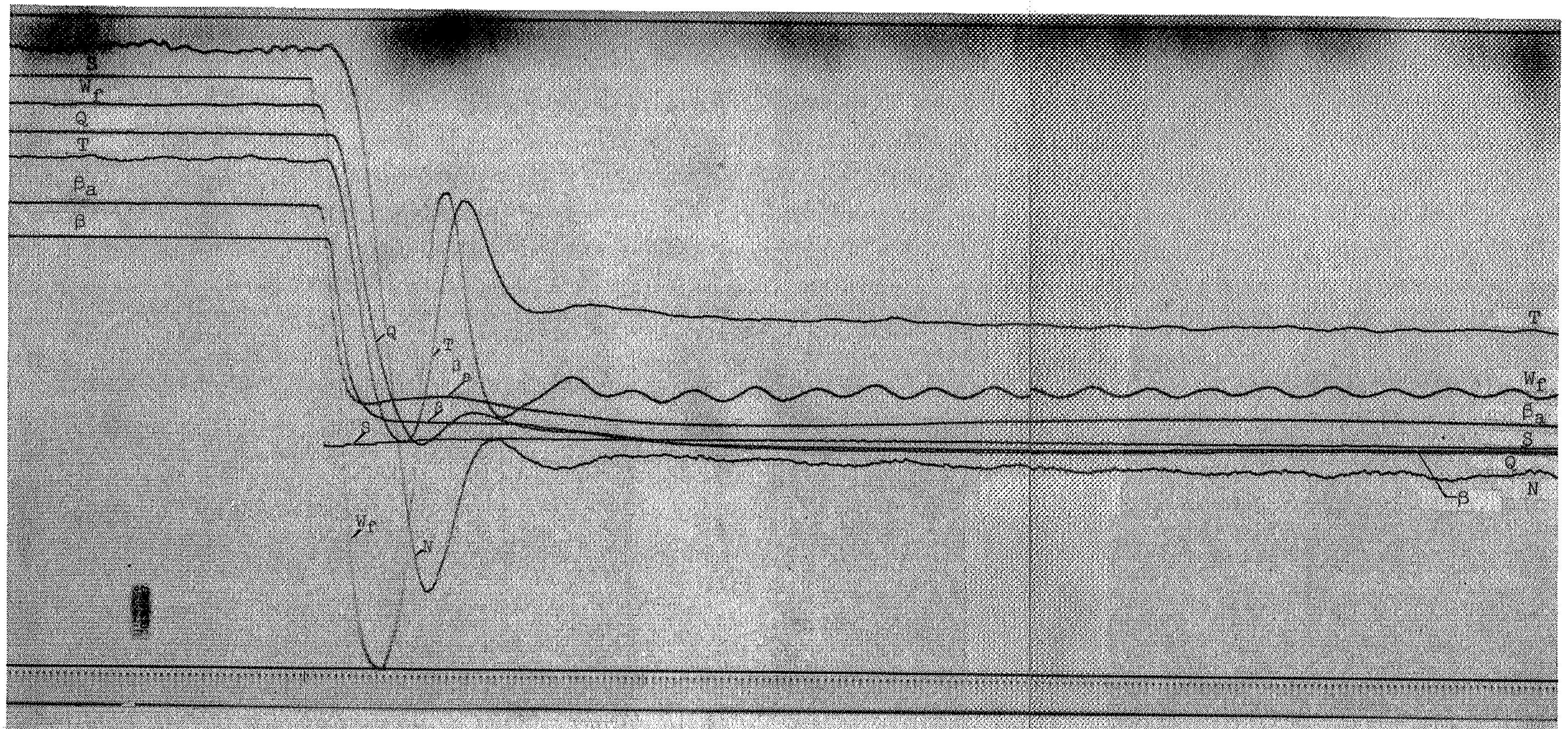
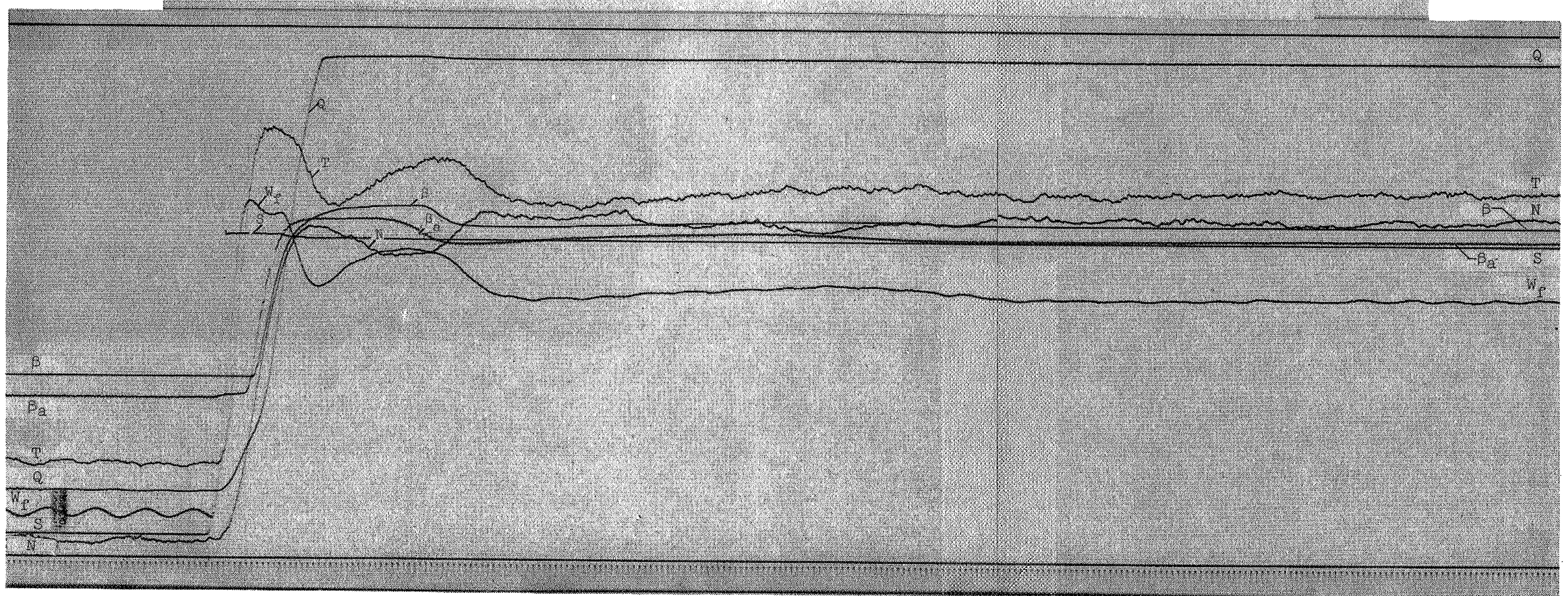


(f) Throttle position, 63.8° to 44.5°.

N_1, 13,300 rpm
S_1, 63.8°
$W_{f,1}$, 1450 lb/hr
Q_1, 549.1 ft-lb
T_1, 1242° F
$\beta_{a,1}$, 52 μa
β_1, 28.35°

N_f, 12,362 rpm
S_f, 44.5°
$W_{f,f}$, 849.5 lb/hr
Q_f, 174.4 ft-lb
T_f, 825.6° F
$\beta_{a,f}$, 29 μa
β_f, 18.55°



N_1, 12,388 rpm
S_1, 44.5°
$W_{f,1}$, 865.2 lb/hr
Q_1, 182.4 ft-lb
T_1, 811.8° F
$\beta_{a,1}$, 31 μa
β_1, 19.2°

N_f, 13,300 rpm
S_f, 63.5°
$W_{f,f}$, 1450 lb/hr
Q_f, 546.1 ft-lb
T_f, 1214° F
$\beta_{a,f}$, 52 μa
β_f, 28.35°

(f) Concluded. Throttle position, 44.5° to [illegible].5°.

Figure 3. - Continued. Transient operation of automatically controlled engine.

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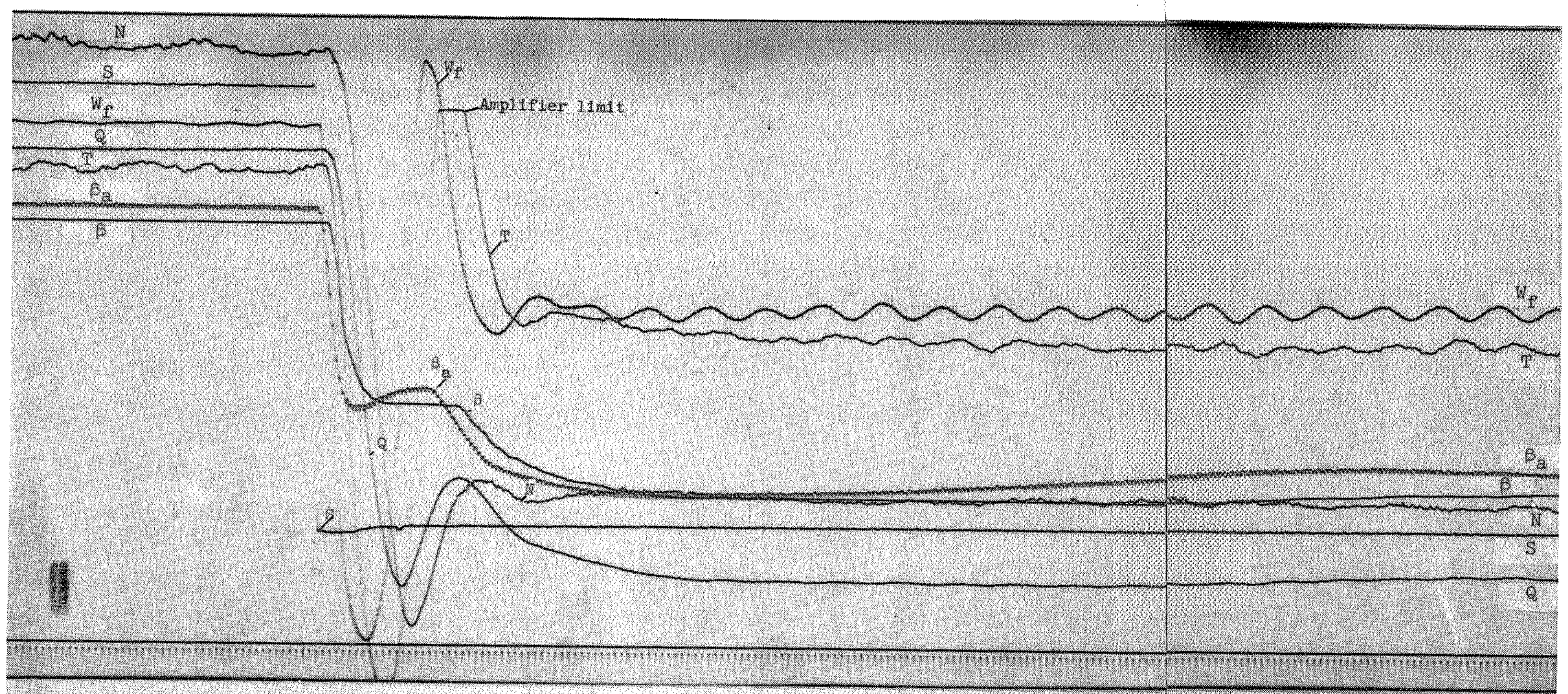
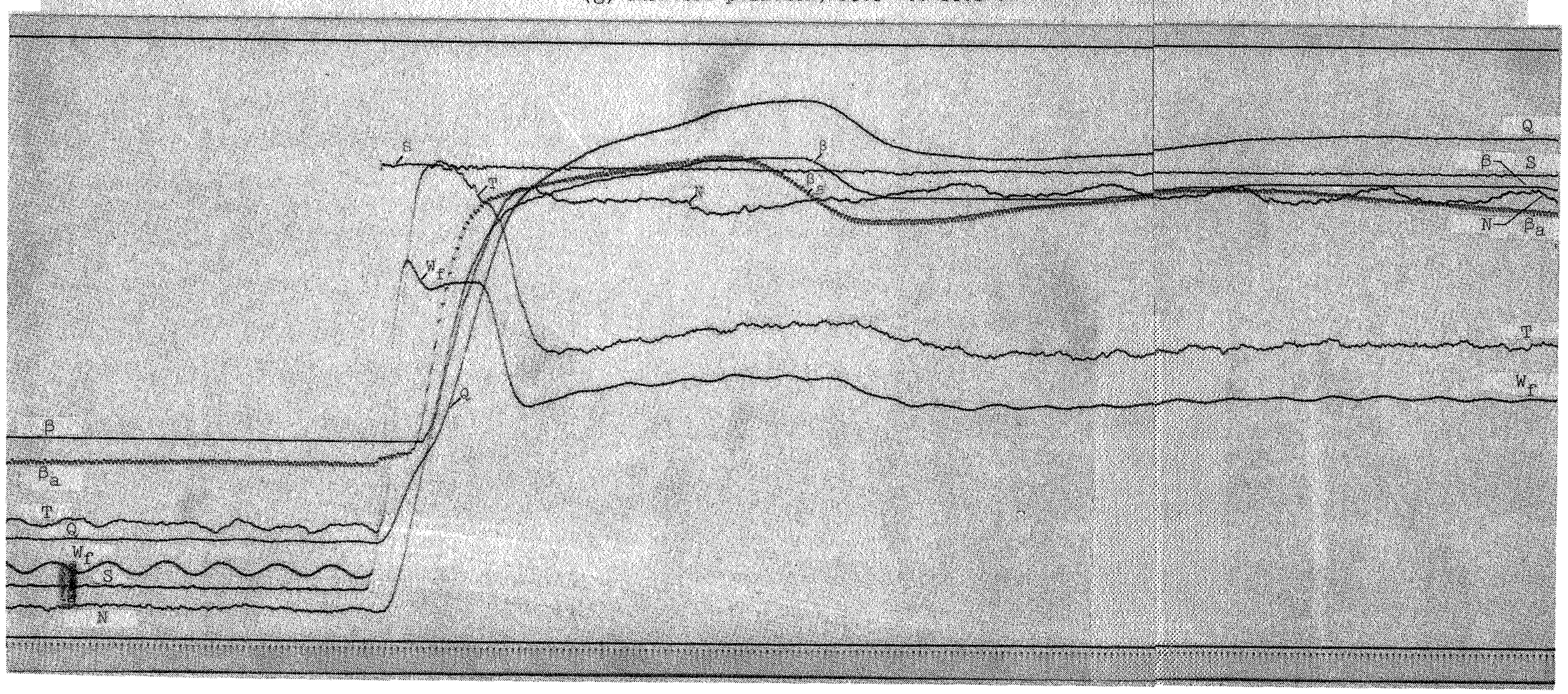


(g) Throttle position, 53.3° to 44.5°.

N_i, 13,382 rpm
S_i, 53.3°
$W_{f,i}$, 1168 lb/hr
Q_i, 348.9 ft-lb
T_i, 913.7° F
$\beta_{a,i}$, 41 μa
β_i, 23.6°

N_f, 12,321 rpm
S_f, 44.5°
$W_{f,f}$, 846.4 lb/hr
Q_f, 176.4 ft-lb
T_f, 811.8° F
$\beta_{a,f}$, 30 μa
β_f, 18.65°



N_i, 12,321 rpm
S_i, 44.5°
$W_{f,i}$, 846.4 lb/hr
Q_i, 171.5 ft-lb
T_i, 803.4° F
$\beta_{a,i}$, 30 μa
β_i, 18.65°

N_f, 13,382 rpm
S_f, 53.8°
$W_{f,f}$, 1177 lb/hr
Q_f, 337.0 ft-lb
T_f, 909.5° F
$\beta_{a,f}$, 40 μa
β_f, 23.6°

(g) Concluded. Throttle position, 44.5° to 53.8°.

Figure 3. - Continued. Transient operation of automatically controlled engine.

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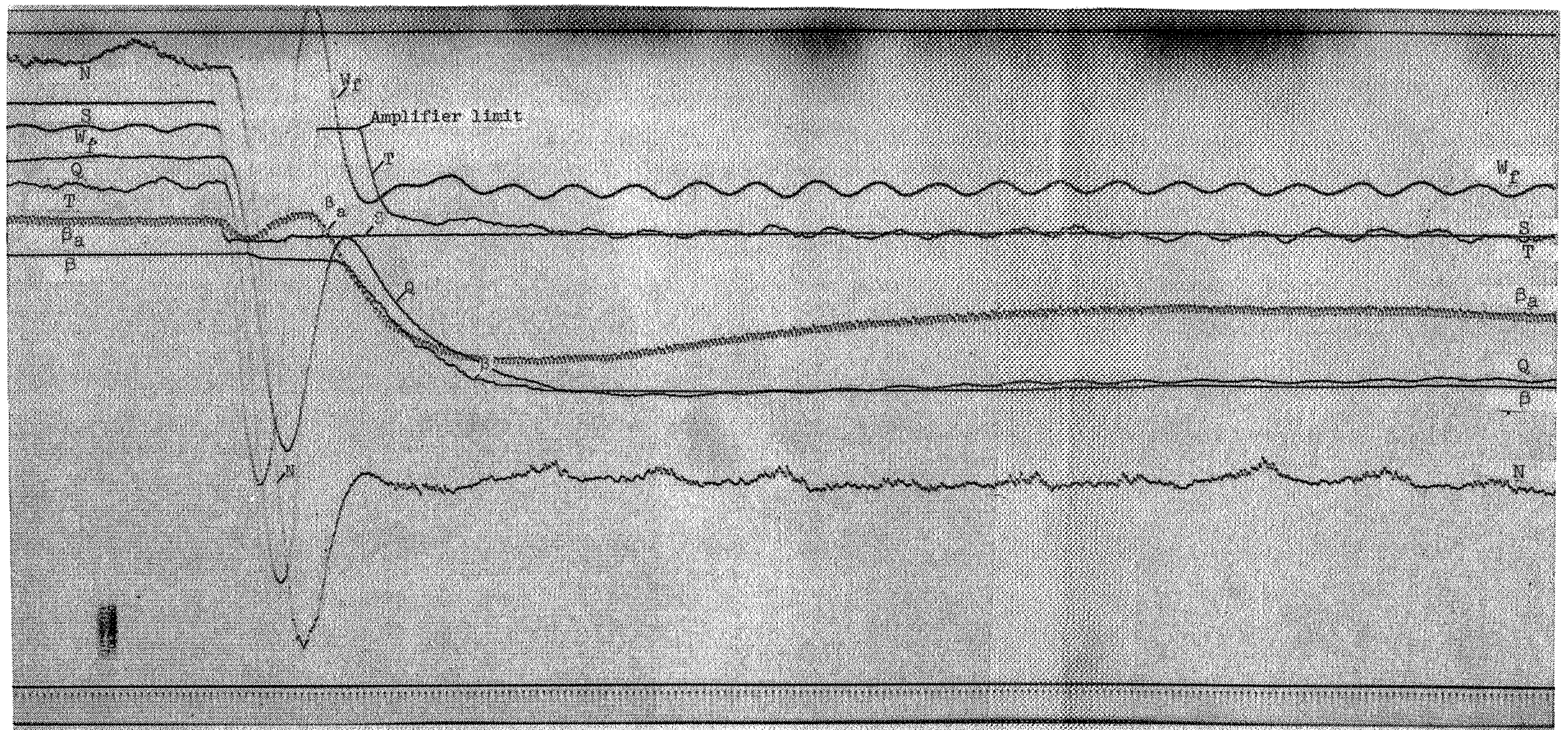
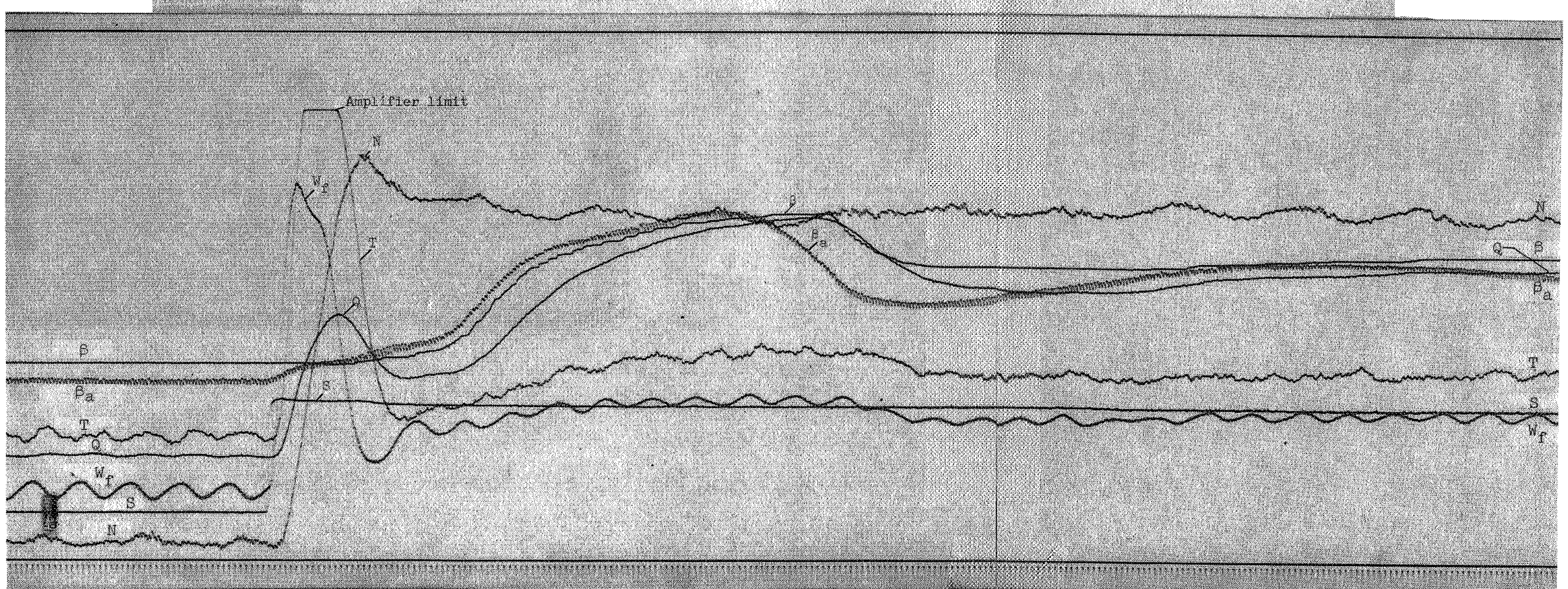


(h) Throttle position, 47.0° to 44.5°.

N_i, 12,877 rpm	N_f, 12,336 rpm
S_i, 47.0°	S_f, 44.5°
$W_{f,i}$, 959.0 lb/hr	$W_{f,f}$, 849.5 lb/hr
Q_i, 220.0 ft-lb	Q_f, 178.4 ft-lb
T_i, 833.1° F	T_f, 808.7° F
$\beta_{a,i}$, 33 μa	$\beta_{a,f}$, 30 μa
β_i, 20.2°	β_f, 18.9°



N_i, 12,336 rpm	N_f, 12,867 rpm
S_i, 44.5°	S_f, 47.0°
$W_{f,i}$, 849.5 lb/hr	$W_{f,f}$, 955.9 lb/hr
Q_i, 174.4 ft-lb	Q_f, 217.0 ft-lb
T_i, 805.5° F	T_f, 832.0° F
$\beta_{a,i}$, 30 μa	$\beta_{a,f}$, 32 μa
β_i, 18.9°	β_f, 20.2°

(h) Concluded. Throttle position, 44.5° to 40°.

Figure 3. - Continued. Transient operation of automatically controlled engine.

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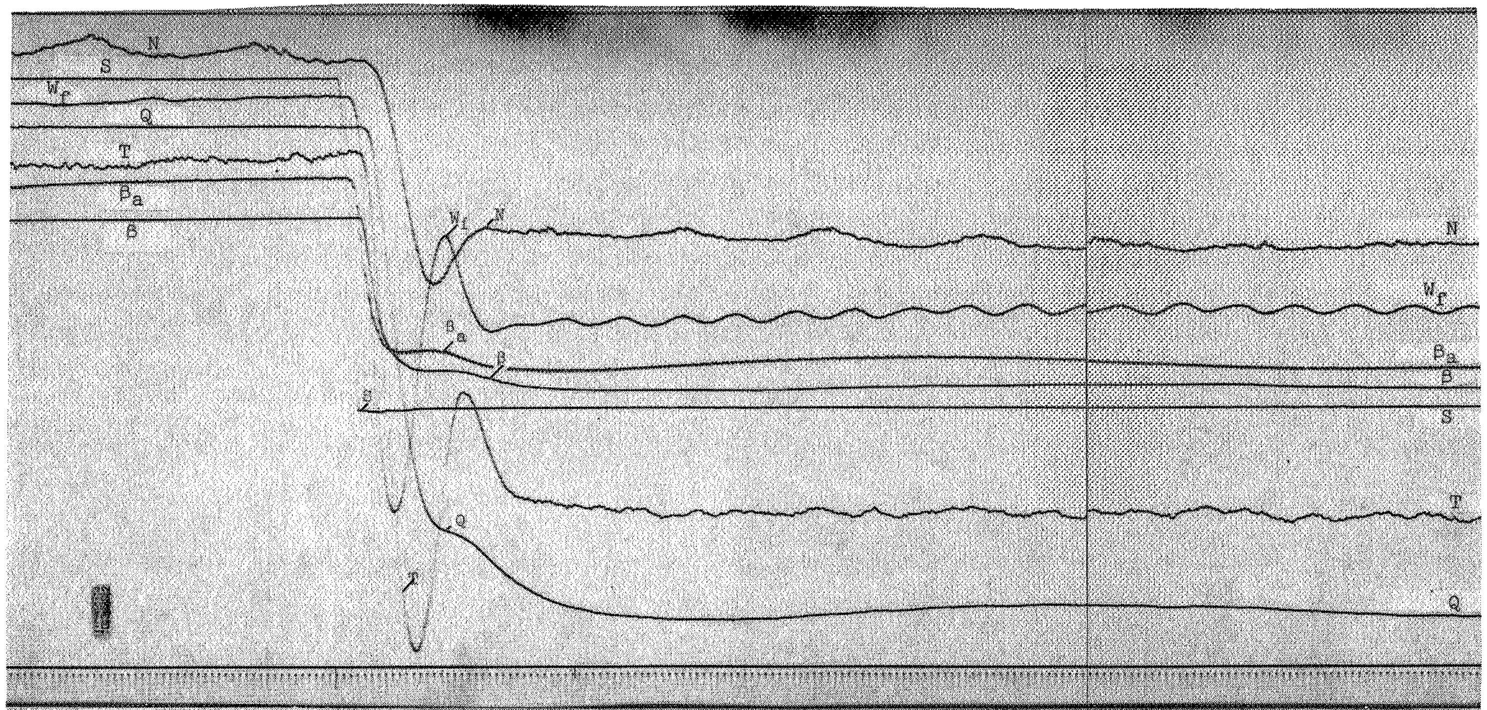
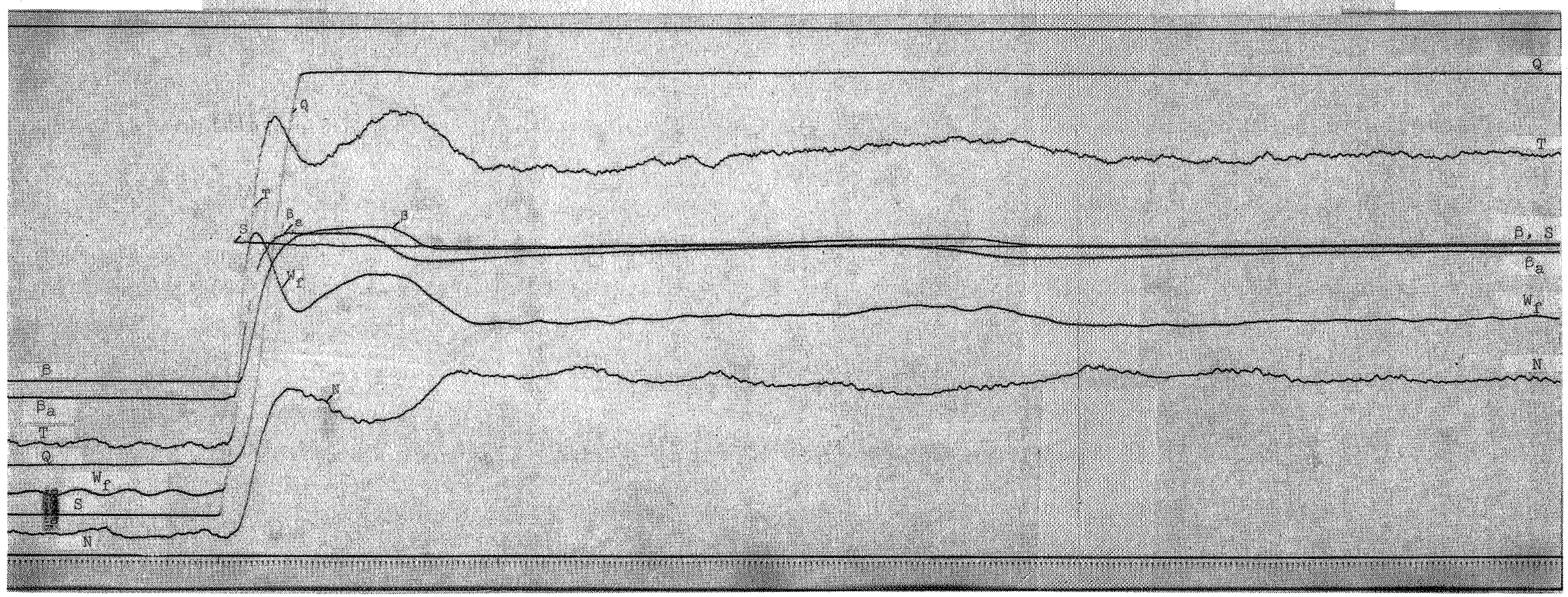


N_i, 13,264 rpm
S_i, 64.5°
$W_{f,i}$, 1469 lb/hr
Q_i, 561.0 ft-lb
T_i, 1263° F
$\beta_{a,i}$, 53 μa
β_i 28.6°

N_f, 12,851 rpm
S_f, 47.0°
$W_{f,f}$, 965.2 lb/hr
Q_f, 228.0 ft-lb
T_f, 860.7° F
$\beta_{a,f}$, 33 μa
β_f, 20.45°

(i) Throttle position, 64.5° to 47.0°.



N_i, 12,851 rpm
S_i, 47.0°
$W_{f,i}$, 965.2 lb/hr
Q_i, 225.0 ft-lb
T_i, 844.7° F
$\beta_{a,i}$, 34 μa
β_i, 20.45°

N_f, 13,264 rpm
S_f, 64.2°
$W_{f,f}$, 1465 lb/hr
Q_f, 561.9 ft-lb
T_f, 1260° F
$\beta_{a,f}$, 52 μa
β_f, 28.6°

(i) Concluded. Throttle position, 47.0° to 64.2°.

Figure 3. - Continued. Transient operation of automatically controlled engine.

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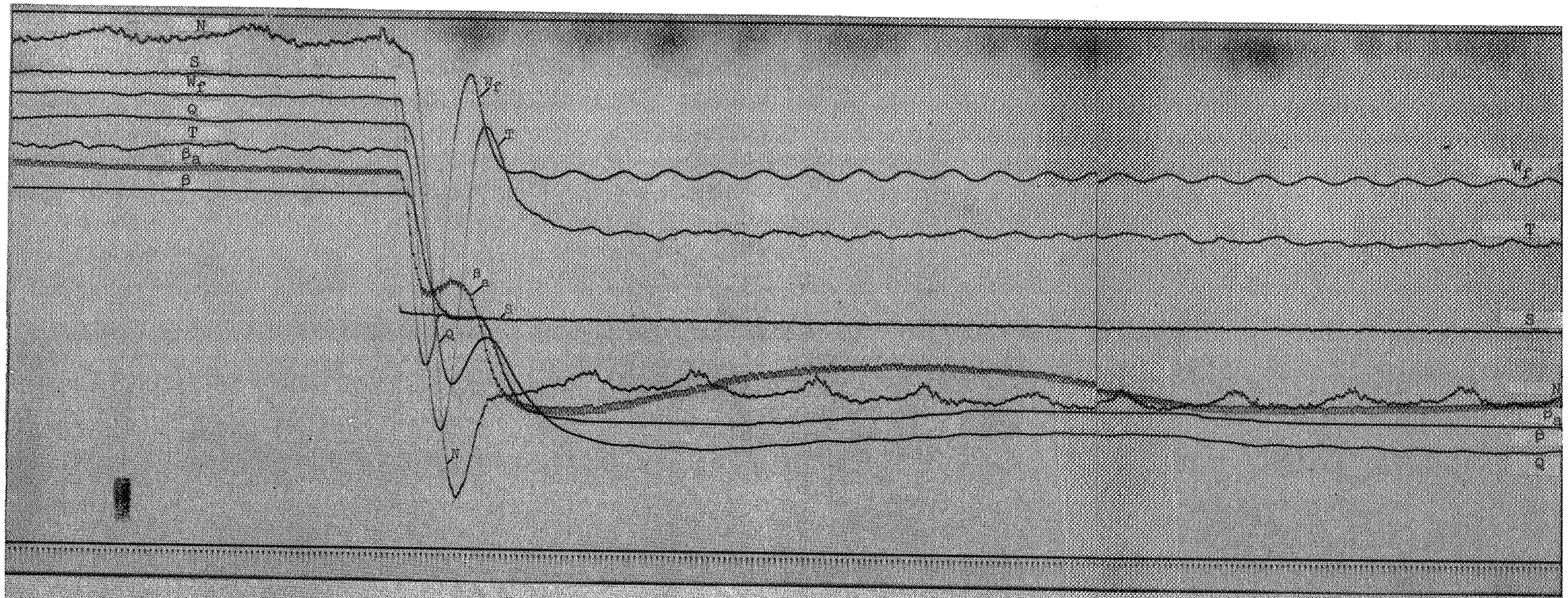
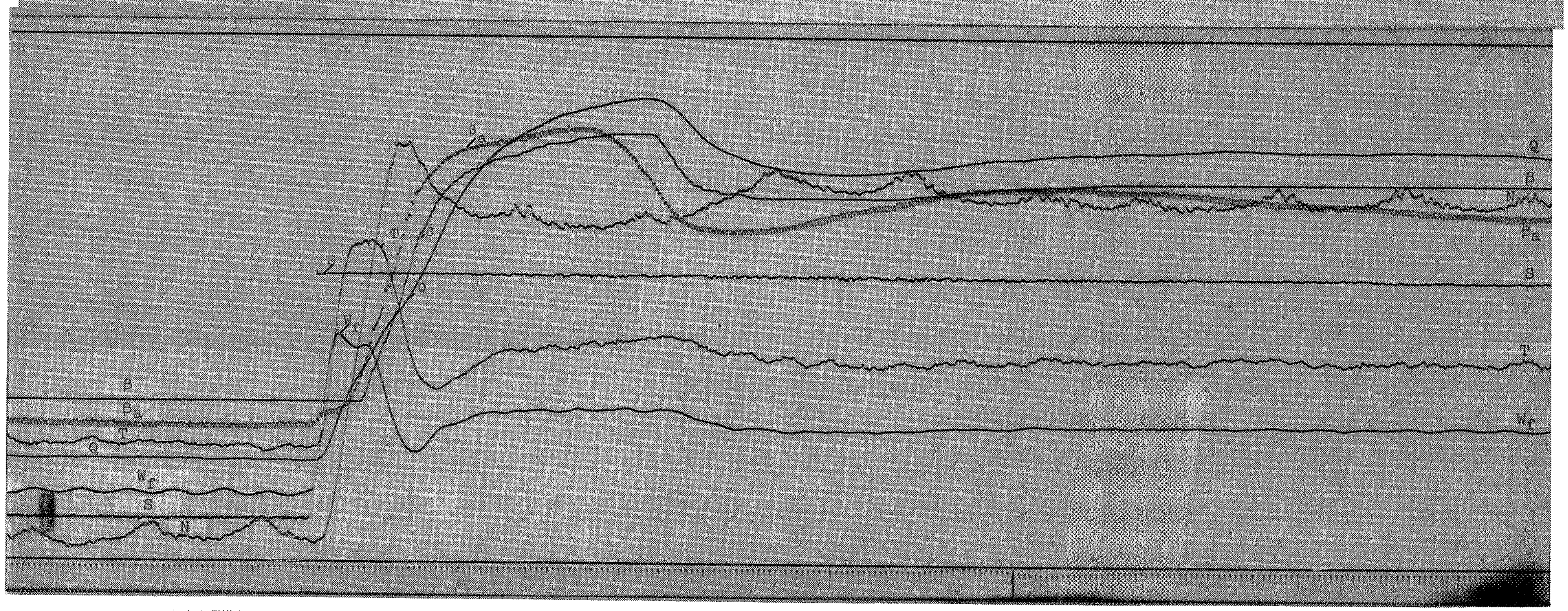


N_i, 13,382 rpm
S_i, 53.3°
$W_{f,i}$, 1149 lb/hr
Q_i, 335.0 ft-lb
T_i, 909.5° F
$\beta_{a,i}$, 40 μa
β_i, 23.15°

N_f, 12,836 rpm
S_f, 47.0°
$W_{f,f}$, 961.1 lb/hr
Q_f, 228.0 ft-lb
T_f, 843.7° F
$\beta_{a,f}$, 34 μa
β_f, 20.45°

(j) Throttle position, 53.3° to 47.0°.



N_i, 12,836 rpm
S_i, 47.0°
$W_{f,i}$, 961.1 lb/hr
Q_i, 226.0 ft-lb
T_i, 838.4° F
$\beta_{a,i}$, 34 μa
β_i, 20.45°

N_f, 13,382 rpm
S_f, 53.0°
$W_{f,f}$, 1155 lb/hr
Q_f, 335.0 ft-lb
T_f, 907.4° F
$\beta_{a,f}$, 40 μa
β_f, 23.15°

(j) Concluded. Throttle position, 47.0° to 53.0°.

Figure 3. - Continued. Transient operation of automatically controlled engine.

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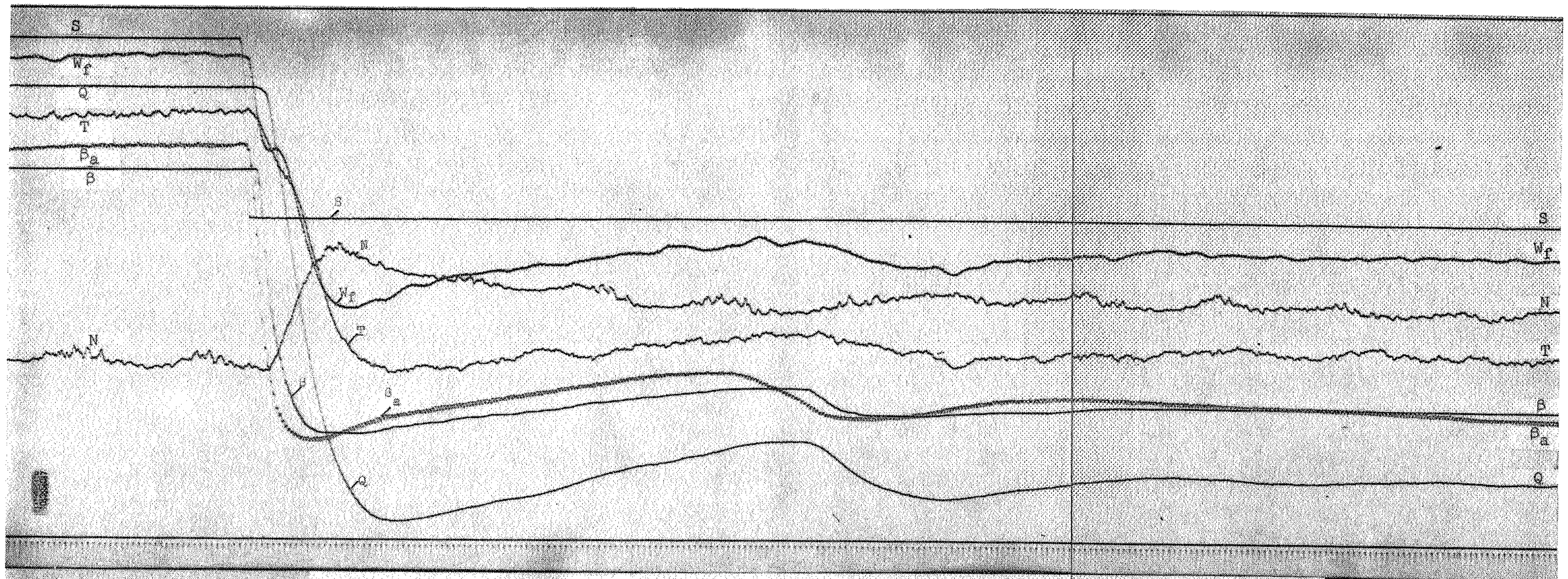
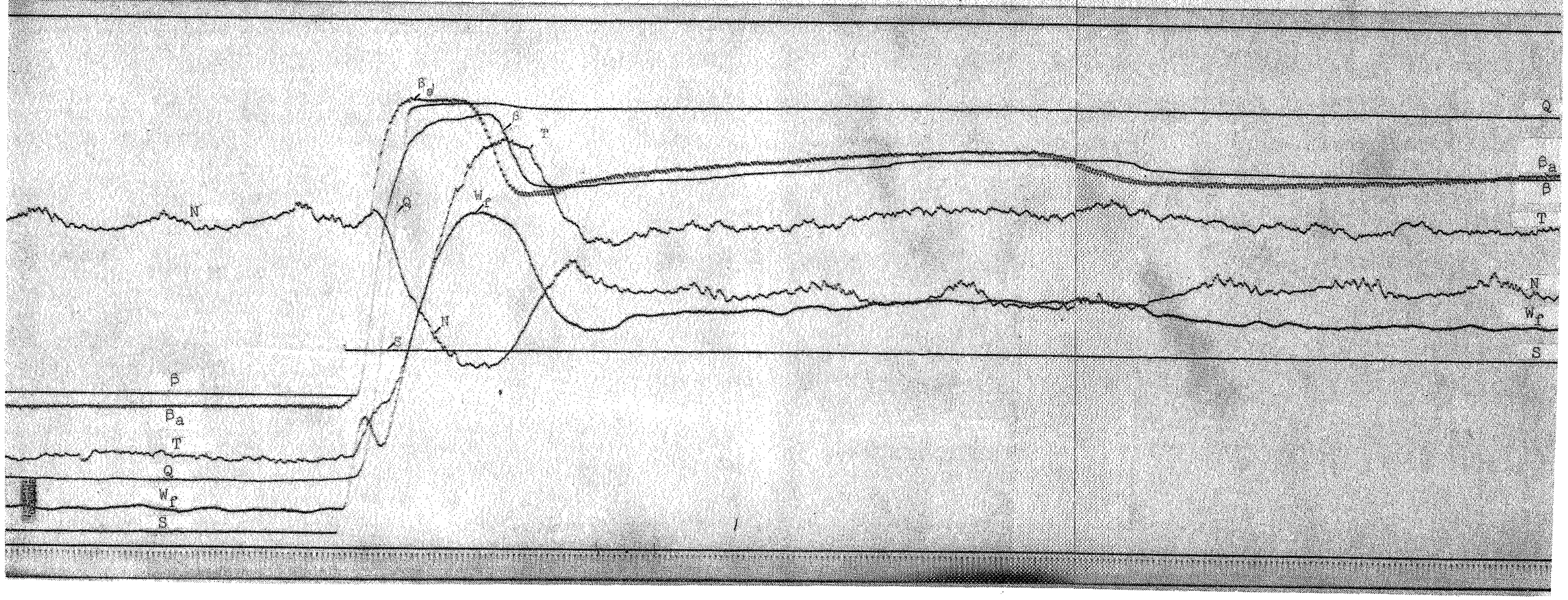


N_i, 13,238 rpm
S_i, 65.0°
$W_{f,i}$, 1475 lb/hr
Q_i, 577.8 ft-lb
T_i, 1321° F
$\beta_{a,i}$, 54 μa
β_i, 29.05°

N_f, 13,315 rpm
S_f, 53.3°
$W_{f,f}$, 1177 lb/hr
Q_f, 349.9 ft-lb
T_f, 944.5° F
$\beta_{a,f}$, 41 μa
β_f, 23.6°

(k) Throttle position, 65.0° to 53.3°.



N_i, 13,315 rpm
S_i, 53.3°
$W_{f,i}$, 1183 lb/hr
Q_i, 356.8 ft-lb
T_i, 939.2° F
$\beta_{a,i}$, 42 μa
β_i, 23.8°

N_f, 13,238 rpm
S_f, 64.5°
$W_{f,f}$, 1475 lb/hr
Q_f, 568.9 ft-lb
T_f, 1302° F
$\beta_{a,f}$, 53 μa
β_f, 28.8°

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(k) Concluded. Throttle position, 53.3° to 64.5°.

Figure 3. - Concluded. Transient operation of automatically controll engine.

CONTROL PERFORMANCE OF GENERAL ELECTRIC FUEL AND TORQUE

REGULATOR OPERATING ON T31-3 TURBINE-PROPELLER

ENGINE IN SEA-LEVEL TEST STAND

Frank L. Oppenheimer

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