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RESEARCH MEMORANDUM

A TEMPERATURE-SCHEDULE ACCELERATION CONTROL FOR A TURBOJET ENGINE AND ITS USE WITH A SPEED CONTROL

By Theodore F. Gerus, Albert G. Powers, and Herbert J. Heppler

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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RESEARCH MEMORANDUM

A TEMPERATURE-SCHEDULE ACCELERATION CONTROL FOR A TURBOJET ENGINE AND ITS USE WITH A SPEED CONTROL

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SUMMARY

A temperature-limiting control was used on a turbojet engine in order to study the feasibility of its use as an acceleration control. A proportional-plus-integral type of control was used in this investigation. Transient response data were obtained to investigate the control-system response and stability. The response was evaluated in terms of temperature-schedule overshoot and acceleration time as a function of control-parameter settings and input disturbance rate.

Both overshoot and acceleration time were found to be functions of rate of input disturbance, schedule level, system gain, and controller time constant. All these parameters, therefore, must be adjusted to provide a compromise between fast acceleration and small overshoot. When the temperature-limiting control was added to a proportional-plus-integral speed - fuel-flow control, the system became very unstable, even though each system by itself was stable. One method of stabilization was attempted and found successful. The gain of the speed loop was decreased for large speed errors, and thus the rate of demand made upon the temperature-limiting loop was decreased. Repeated accelerations and decelerations over a short period of time ("go-around") were tried, and even though the temperature-schedule overshoot was slightly larger on cycles after the first than on the first cycle, the difference was slight and there was still no danger of stall or surge.

INTRODUCTION

Two general types of turbojet acceleration control systems have been investigated at the NACA Lewis laboratory. One utilizes the optimalizing technique, which requires an engine-parameter signal to warn of impending stall. This method may be desirable because maximum acceleration could be safely attained independent of altitude corrections and engine deterioration. However, a preliminary investigation (ref. 1) to search for an

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adequate stall warning proved unsuccessful. Until an adequate stall warning is found, other types of acceleration controls must be used.

The second type of control automatically limits engine parameters such as fuel flow, acceleration, compressor discharge pressure, or temperature according to a predetermined schedule. An investigation of a temperature-schedule acceleration control that uses a constant-reference-temperature schedule is presented in reference 2. Since the stall and surge temperatures are a function of speed, however, a constant-reference-temperature schedule cannot give optimum performance. Therefore, an experimental program was conducted with temperature scheduled as a function of engine speed. This schedule was shaped to skirt the stall and surge region. A study of the margin necessary between the schedule and stall temperatures was made for several influencing factors such as the input disturbance rate and control variations. In order to test the practicality of the accelerating control, a speed - fuel-flow control was added to study the operation of the combined system. 4643

CONTROL SYSTEMS

Temperature-Limiting Control

A block diagram of the temperature-limiting control is shown in figure 1(a). A demand signal simulates a signal from the operator to accelerate. This signal sets the desired fuel flow to the engine. Tailpipe temperature is measured and frequency compensated by the temperature-sensor circuit. Speed is measured by the speed sensor, and the measured voltage is applied to the function generator unit to provide the temperature-limiting schedule. The compensated temperature signal is compared with scheduled temperature, and the resulting temperature error serves as an input signal to the temperature controller. The action of the controller is proportional-plus-integral to produce a desired fuel-flow correction. However, the proportional-plus-integral control is in parallel with a low-gain proportional circuit (fig. 1(b)), and thus the output is limited to values that decrease fuel flow (negative values). The operation of this circuit can be explained with the following equations (symbols are defined in the appendix). When $V_o < 0$, the diode does not conduct, and

$$V_o(s) = -P_1 \frac{R_2}{R_1}\left(1 + \frac{1}{R_2 Cs}\right)V_i(s)$$

When $V_o > 0$, the diode conducts, and

$$V_o(s) = -P_1 \frac{R_3}{R_1} \frac{(1 + R_2Cs)}{1 + (R_2 + R_3)Cs} V_i(s)$$

Since R_3 is much less than R_2 or R_1, the positive output is negligible.

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Two-Loop Control

A block diagram of the speed control and temperature-schedule acceleration control combined is shown in figure 2(a). The action of the temperature loop in the two-loop control is exactly the same as in the temperature-limiting control. The demand on the combined system is made in the form of a speed demand, however, rather than a fuel-flow demand. In the speed-control loop, engine speed is sensed and compared with the reference speed. The speed error is operated on by a proportional-plus-integral control that governs the demand fuel flow. When the speed error gets larger than a preset value, the gain of the control is decreased to stabilize the two-loop system. A schematic diagram of the stabilizing unit used for this purpose is shown in figure 2(b). The operation of this nonlinear element can be explained as follows. When $V_o' < P_3E$, the diode does not conduct, and

$$V_o' = \frac{R_2'}{R_1'} V_i'$$

When $V_o' > P_3E$, the diode conducts, and

$$V_o' = \frac{P_3E}{1 + \frac{R_3'}{R_1'}} + \frac{R_2'/R_1'}{1 + \frac{R_2'}{R_3'}} V_i'$$

Since $R_2' > R_3'$, there is a large decrease in gain when $V_o' > P_3E$.

COMPONENT DYNAMICS

Sensors

Tailpipe temperature. - Three sets of four thermocouples spaced to give an average temperature were used to measure tailpipe temperature. These high-temperature thermocouples were made of 18-gage Chromel-Alumel wire and responded with an approximate first-order lag with a time constant which varied with engine speed from 0.63 to 0.33 second (fig. 3).

A thermocouple compensator of a lead-lag-lag nature was used to extend the thermocouple frequency response. A fixed compensator lead time constant of 0.605 second and lag time constants of 0.01 and 0.005 second were used. The lead term was used to compensate the thermocouple lag, and the lag terms were used as high-frequency filters. The compensated thermocouple response was flat to 16 cycles per second at an engine speed of 4250 rpm and overcompensated at higher speeds.

Engine speed. - A voltage proportional to speed was obtained by electronic conversion of pulses obtained from a magnetic pickup installed in the compressor housing opposite a row of compressor blades. The pickup and electronic circuit had no measurable dynamics in the range of interest. 4643

Fuel System

Fuel was fed to the engine manifolds through a differential-reducing-valve type of flow regulator that maintains a constant pressure drop across a throttle. The response of this valve system was flat to 100 cycles per second. The throttle area was varied by an electro-hydraulic servomotor. The response of this unit to an input voltage was essentially flat to 20 cycles per second. The control system thus varied the fuel flow by varying the voltage impressed upon the electro-hydraulic servomotor. A signal proportional to the throttle area was calibrated and used for transient fuel-flow measurements. (A complete description of this system is given in ref. 3.)

Engine

Tailpipe-temperature - fuel-flow response. - Because acceleration transient times are relatively short, about 1 second to the first overshoot and about 5 seconds for the complete transient, the ability of the system to follow an accelerating schedule depends on the higher frequency characteristics of the engine response. The lowest pertinent frequencies are about 1/2 cycle per second during the transient; thus the engine temperature - fuel-flow responses below 0.1 cycle per second were not considered. The steady-state gain reversal at engine speeds of about 6100 rpm is not a factor. Temperature - fuel-flow frequency response was found experimentally. The amplitude and phase-shift frequency response above 0.1 cycle per second at an engine speed of 4500 rpm is given in figure 4. Also given in figure 4 is the amount of the phase shift resulting from dead time. Dead time was found experimentally from responses to step disturbances. The transfer function which approximately fits the compensated frequency response is

$$KG_{tw}(s) = \frac{K_{tw}(1 + \alpha_{tw}s)e^{-t_{d-t}s}}{(1 + \tau_{tw,1}s)(1 + \tau_{tw,2}s)}$$

Variations of $\tau_{tw,1}$, $\tau_{tw,2}$, and α_{tw} with speed are given in figure 5. Variation of K_{tw} with speed is given in figure 6. Variation of dead time with speed is given in figure 7.

Speed - fuel-flow response. - The dynamics of the speed - fuel-flow response resemble a first-order lag plus dead time in the frequency range of interest. Variation of steady-state speed with fuel flow is given in figure 8. The speed - fuel-flow gain can be determined from this curve. The variation of lag time constant (τ_{nw}) with speed is shown in figure 9. Speed - fuel-flow dead time is shown in figure 10.

Surge and stall limits. - Data were taken to determine the tailpipe temperature when the engine first went into stall or surge after a large step disturbance in fuel flow. Figure 11 shows a number of these points at various speeds. The schedules used in the temperature-limiting control and the steady-state map are shown in relation to these points.

PROCEDURE AND RANGE OF VARIABLES

The experimental program consisted of engine accelerations controlled by (1) the temperature-limiting control and (2) the combination temperature-limiting and speed-error control.

Transient data were recorded on a direct-reading oscillograph, the frequency response of which was essentially flat to 100 cycles per second. Also used to record "go-around" (full-range acceleration and deceleration) was an X-Y plotter in which a speed signal was fed into the arm and a tailpipe-temperature signal was fed into the pen.

One-Loop Control

A ramp input in fuel flow was used as a demand signal to determine the performance of the temperature-limiting control. The transients were initiated at an engine speed of 4000 rpm (idle), and the following parameters were varied individually: (1) ramp rate of disturbance, (2) schedule-level bias, (3) controller gain, and (4) controller time constant. The ramp rate of disturbance was varied between 500 and 6500 pounds per hour per second and was held constant at 2840 pounds per hour per second when other parameters were varied. Figure 11 shows the extremes in schedule level and the intermediate schedule level kept when the other parameters were varied. The schedule is shown in relation to steady-state and stall and surge points.

Evaluation of the control system and its parameters was made from the following criteria:

(1) Stability limits

(2) Temperature-schedule overshoot

(3) Acceleration time

Two-Loop Control

The speed - fuel-flow control was set to a compromise of fast response and small overshoot at a speed midway between idle and rated. At this speed the engine dynamics were nearly a median of the range of variation in engine dynamics from idle to rated speed. The two control loops were then combined, and ramp disturbances in the demand speed were applied. The nonlinear stabilizing-unit-component gains were varied individually to produce variation of the fuel-flow demand rate at the time the temperature crossed the schedule limit. The fuel-flow demand rate was varied between 900 and 2800 pounds per hour per second to find a limit where the two-loop system would be stable.

Also run were "go-around" tests to discover any possibility of stall or surge after several cycles and to determine whether the temperature-schedule overshoot would vary.

RESULTS AND DISCUSSION

Temperature-Limiting Control

A typical acceleration transient is shown in figure 12. The recorded traces are speed, fuel flow, tailpipe temperature, controller output, and demand signal. Superimposed upon the tailpipe-temperature signal is the temperature schedule. From steady-state operation at 4000 rpm a fuel-flow disturbance of 2840 pounds per hour per second is applied until nearly rated fuel flow is reached. The fuel flow increases as a ramp for approximately 0.62 second, until the temperature reaches the schedule. When the temperature exceeds the schedule, the controller output calls for a reduction in fuel flow. However, the temperature must continue to rise from the time it first reaches the schedule until the end of the dead time (t_{d-t}), which produces an irreducible overshoot accounting in general for about 75 percent of the total overshoot. The temperature then responds to the difference between the fuel-flow disturbance and the controller output, which occurred t_{d-t} earlier in time.

Stability limits. - Figure 13 shows typical transient data for the control system when it becomes unstable during a portion of the transient. Experimental and theoretical system stability limits are shown in figure 14 for accelerations in which controller gain and time constant were varied. The theoretical stability limit is based upon engine dynamics at 4500 rpm. For controller time constants above 0.3 second the controller stability limit in gain is approximately 0.2. This represents a loop gain of 1.8. Making the time constant of the controller small enough to approach the upper-frequency temperature - fuel-flow lag time constant ($\tau_{tw,2}$) decreases the maximum allowable proportional gain. However, decreasing the controller time constant also increases the frequency range of the integrator action. Therefore, within this range the response will be improved.

Overshoot and acceleration time. - Maximum overshoot and acceleration time are plotted against controller gain and time constant in figure 15. A long time constant (0.25 sec) and a low gain (0.052) produce high schedule overshoot and small acceleration time. In the case illustrated by figure 16 the overshoot is so great that the engine stalls. With the other extreme, with a short time constant (0.025 sec) and the same gain, the system is unstable (fig. 13). However, when the controller time constant is slightly longer than $\tau_{tw,2}$ (e.g., 0.125 sec) overshoot is nearly minimized, and acceleration time is still reasonable.

Calculations were made to find the schedule overshoot analytically. Component dynamics as given previously were used with the exception that engine dynamics were approximated as follows:

$$KG'_{tw}(s) = \frac{K_{tw}\alpha_{tw}/\tau_{tw,1}\; e^{-t_d - t^s}}{(1 + \tau_{tw,2}s)}$$

The calculated values were accurate for only a limited range of overshoot because of nonlinearities a great distance from the steady-state line. The following are examples of predicted and experimental overshoot:

Temperature-controller time constant	Temperature-controller gain	Experimental overshoot, °F	Calculated overshoot, °F
0.125	0.052	160	129
	.078	102	113
	.156	96	100
	.208	96	93
0.25	0.156	154	133
	.208	101	95

In the above overshoots, the overshoot due to dead time alone is about 75° F.

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Figure 17 illustrates the effects of ramp rate of disturbance on schedule overshoot and acceleration time. The schedule overshoot varies nearly linearly with ramp rate because most of the overshoot is due to dead time. The acceleration time is not highly affected by a change in ramp rate except for small ramp rates.

Figure 18 shows the effects of schedule level on acceleration time and overshoot. The level of the schedule has a very large effect on the acceleration time. However, with increasing schedule level, the danger of stall and surge becomes more imminent because the schedule is closer to the stall and surge line, and, in addition, the overshoot is greater. On the plot of schedule overshoot against schedule level in figure 18 the overshoot increases sharply with a rise in schedule level after a definite level. This is believed to be due to a reaching of a point of nonlinearity of the engine close to the stall and surge line.

Figure 19 is a trace of the engine going into a stall because of high schedule level. At stall the temperature jumps to a much higher level, which results in fuel reduction by the temperature-limiting control. Upon recovery from stall, fuel flow again increased, overshoot occurred, and a second stall resulted. The temperature control again recovered the engine from stall and prevented further stalling. This illustrates a feature of this control, that even if the engine goes into stall, the large increase in temperature caused by stall will tend to reduce the fuel flow and permit stall recovery.

Two-Loop Control

Since the largest problem occurring when the temperature-limiting acceleration loop and the speed loop are connected is instability, control-parameter settings may be evaluted with reference to stability.

The system could be stabilized by limiting the rate of demand made upon the temperature control. Since this rate depends primarily on the rate of change of fuel flow at the time the temperature crosses the schedule, alterations of this fuel-flow rate were made automatically without affecting normal speed control by using a nonlinear gain in the speed controller.

Approximately 1200 pounds per hour per second was the highest fuel-flow rate that the temperature control could allow and yet remain stable. Thus, for stability the nonlinear amplifier must reduce the fuel-flow demand to this value at the instant the limiting action commences. As a demonstration of this, figure 20 shows a case of instability with a nonlinear gain in the speed circuit and a ramp rate upon entry of the schedule of 1260 pounds per hour per second. Figure 21 shows a case of stability with nonlinear gain in the speed circuit and a ramp rate at entry of the schedule of 1197 pounds per hour per second. (Recorded traces are speed, fuel flow, tailpipe temperature, temperature-controller output, and speed error or disturbance.)

"Go-Around" Runs

Several repeated acceleration and deceleration disturbances were placed upon the control to demand the full range of speeds (idle to near rated). Figure 22 shows the trace of tailpipe temperature against speed recorded on an X-Y plotter during several "go-around" runs. Even though temperature overshoot increased slightly after the first "go-around", no surge or stall could be detected during seven cycles of acceleration and deceleration with a conservative schedule level of 325° F above steady-state temperature at 4000 rpm. Apparently the schedule was far enough from the stall and surge line that no effects were produced by any lowering of the stall and surge line. Use of the conservative schedule level increased the acceleration time from 4000 to 6500 rpm only 0.8 second over the minimum of 3.4 seconds attained with a high schedule level.

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SUMMARY OF RESULTS

A temperature-limiting control was used on a turbojet engine to study its performance as an acceleration control. The following results were obtained:

When using the temperature-limiting control alone, open-loop gain is limited to a maximum of 1.8 for a stable proportional control (measured above 0.1 cps at 4500 rpm). The major part of the phase shift that causes instability is due to dead time.

A compromise between overshoot and acceleration time is required for all settings of controller gain and time constant, demand rate, and schedule level.

Temperature-limiting control has the desirable feature of tending to bring the engine out of stall or surge if stall or surge are encountered.

Two-loop control can be unstable when each loop separately is stable. Stabilization can be attained by inserting a nonlinear gain in the speed-control loop without affecting normal speed control.

Temperature-schedule-overshoot variations with a number of cycles of "go-around" with the two-loop control are not appreciable. Seven cycles of "go-around" were attained with a conservative schedule level (325° F above steady-state temperature at 4000 rpm), and no stall or surge occurred. By use of the conservative schedule level the acceleration time from 4000 to 6500 rpm is made 0.8 second longer than the minimum of 3.4 seconds attained with a high schedule level.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics 4643
Cleveland, Ohio, September 19, 1957

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APPENDIX - SYMBOLS

C	capacitive component
E	battery voltage
K_{tw}	measured-tailpipe-temperature - fuel-flow gain above 0.1 cps
N	engine speed
P	potentiometer setting
R	resistive element
s	operational form of Laplace operator
T_m	measured tailpipe temperature, $^{\circ}F$
T_s	scheduled tailpipe temperature, $^{\circ}F$
t_{d-t}	tailpipe-temperature - fuel-flow dead time
V	amplifier input or output voltage
W_c	temperature-controller output
α_{tw}	measured-tailpipe-temperature - fuel-flow lead time constant
τ_{tw}	measured-tailpipe-temperature - fuel-flow lag time constant

Subscripts:

i	input
o	output
1,2,3	designation of resistor, capacitor, potentiometer, or lag time constant as noted in diagrams

Superscript:

'	nonlinear stabilizing unit

Transfer Functions:

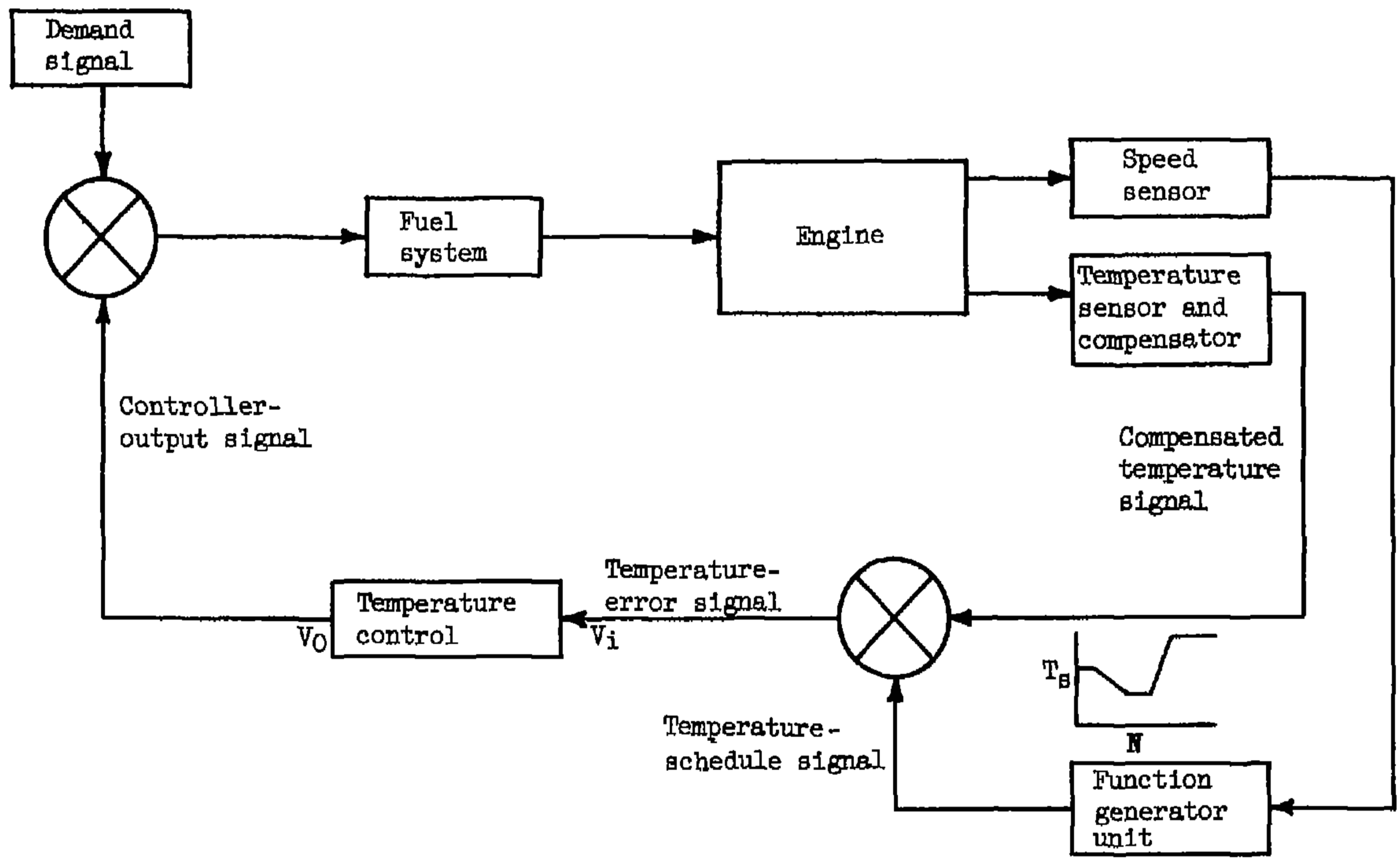
$KG_{tw}(s)$	measured-tailpipe-temperature - fuel-flow dynamics above 0.1 cps
$KG'_{tw}(s)$	measured-tailpipe-temperature - fuel-flow dynamics (approximated)

REFERENCES

1. Novik, David, Heppler, Herbert, and Stiglic, Paul M.: Experimental Investigation of a Surge Control on a Turbojet Engine. NACA RM E55H03, 1955.

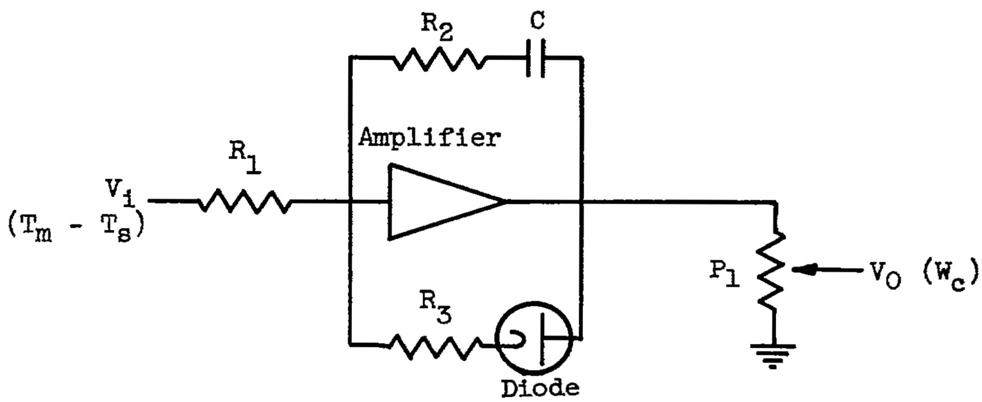
2. Heppler, Herbert, Stiglic, Paul M., and Novik, David: Analytical and Experimental Investigation of a Temperature-Schedule Acceleration Control for a Turbojet Engine. NACA RM E56C08, 1956.

3. Otto, Edward W., Gold, Harold, and Hiller, Kirby W.: Design and Performance of Throttle-Type Fuel Controls for Engine Dynamics Studies. NACA TN 3445, 1955. 4643



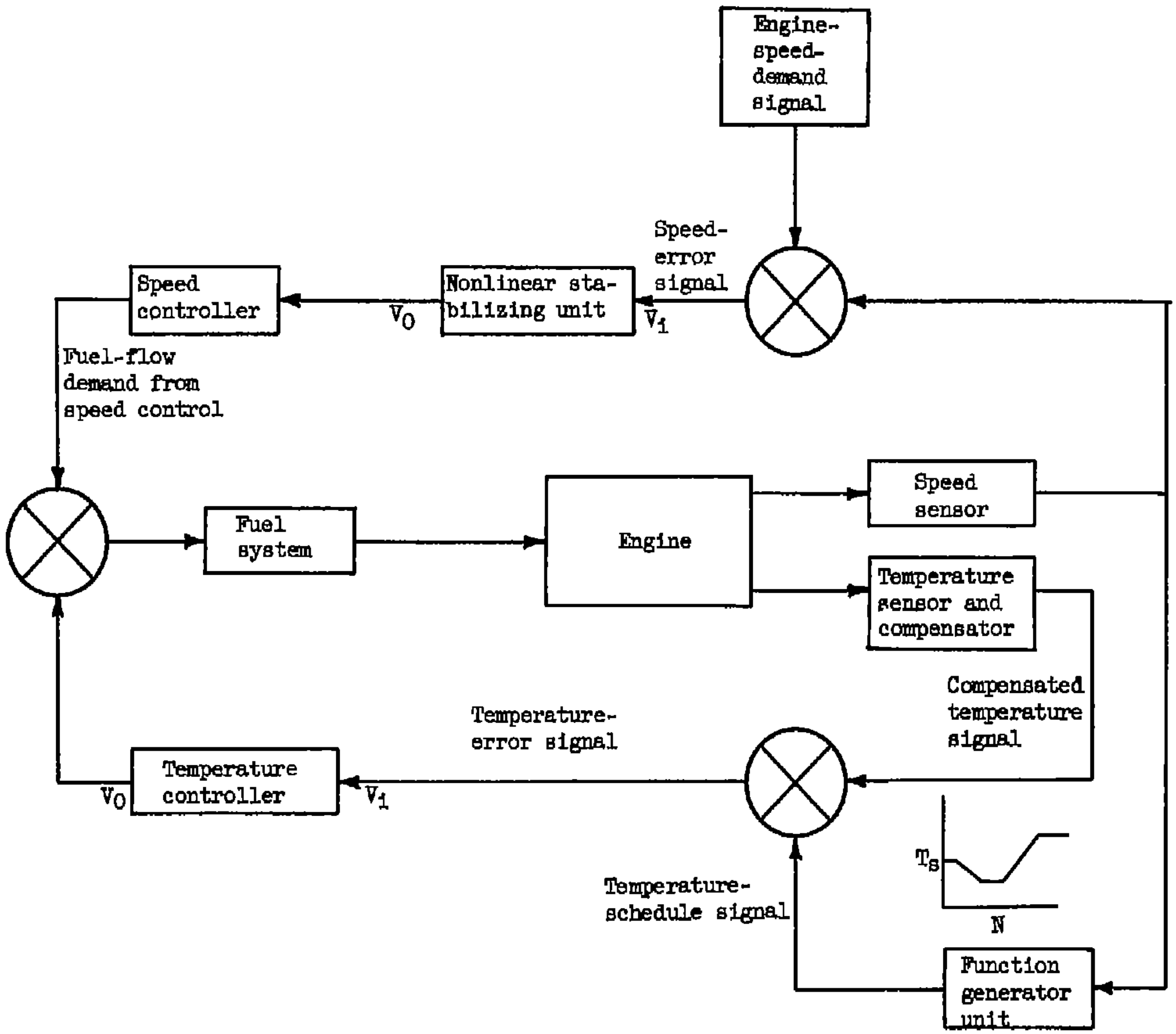
(a) Block diagram of temperature-limiting control.

Figure 1. - Control loop for temperature-schedule acceleration control.



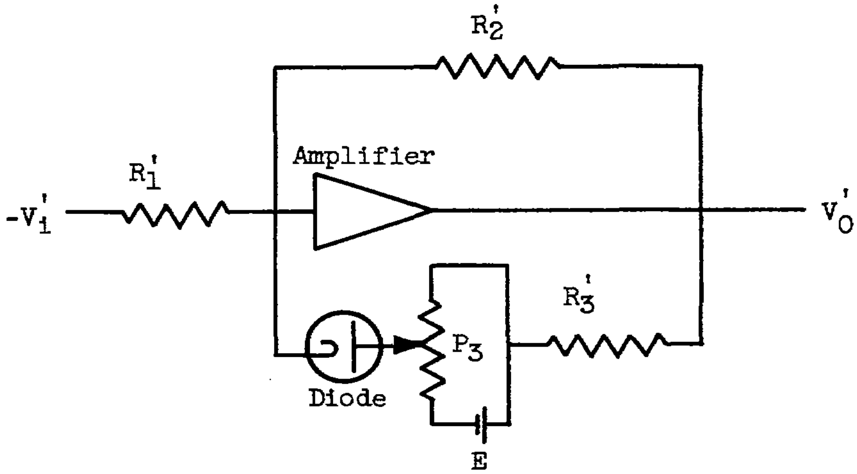
(b) Schematic diagram of nonlinear control.

Figure 1. - Concluded. Control loop for temperature-schedule acceleration control.



(a) Block diagram.

Figure 2. - Control loops for temperature-schedule acceleration control and speed control.



(b) Schematic diagram of nonlinear stabilizing unit.

Figure 2. - Concluded. Control loops for temperature-schedule acceleration control and speed control.

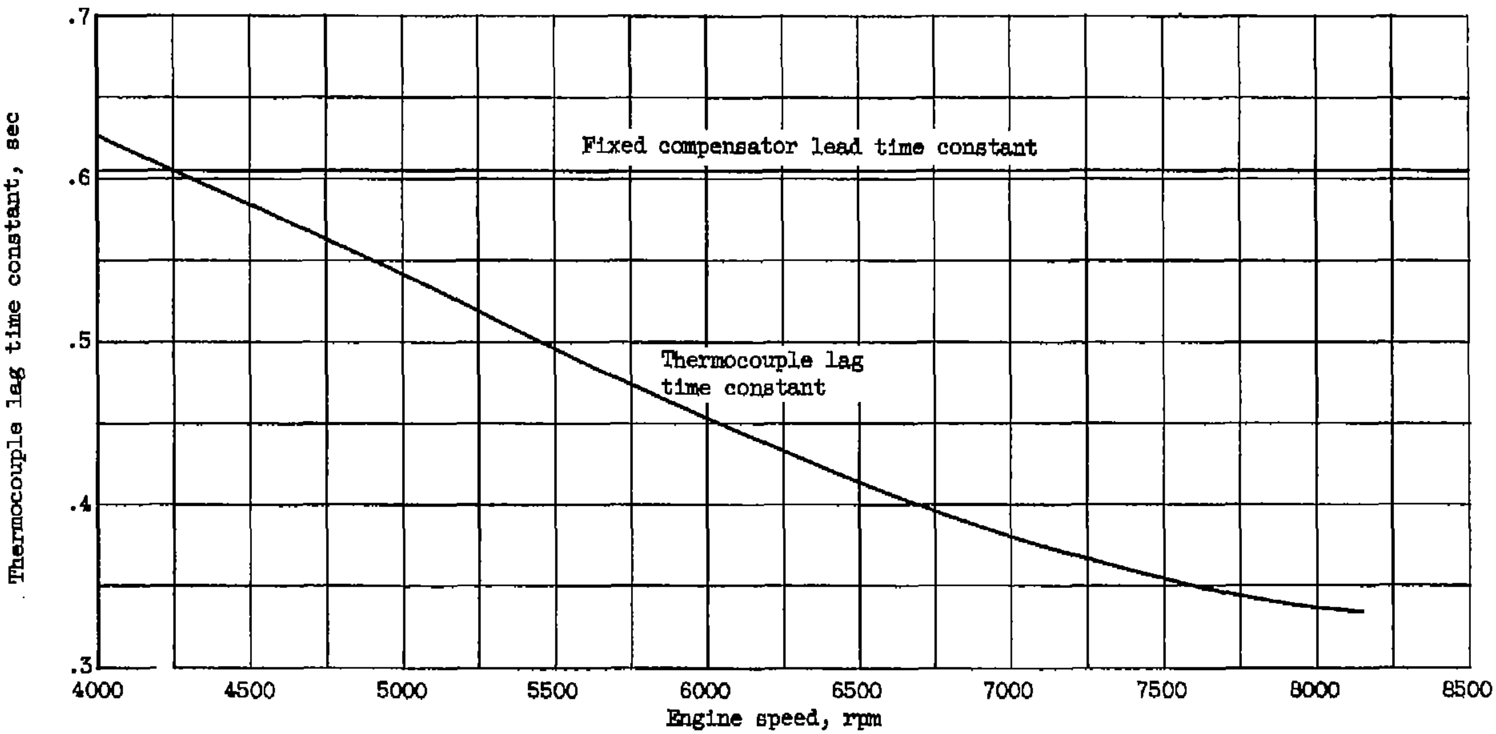


Figure 3. - Variation of thermocouple lag time constant with engine speed.

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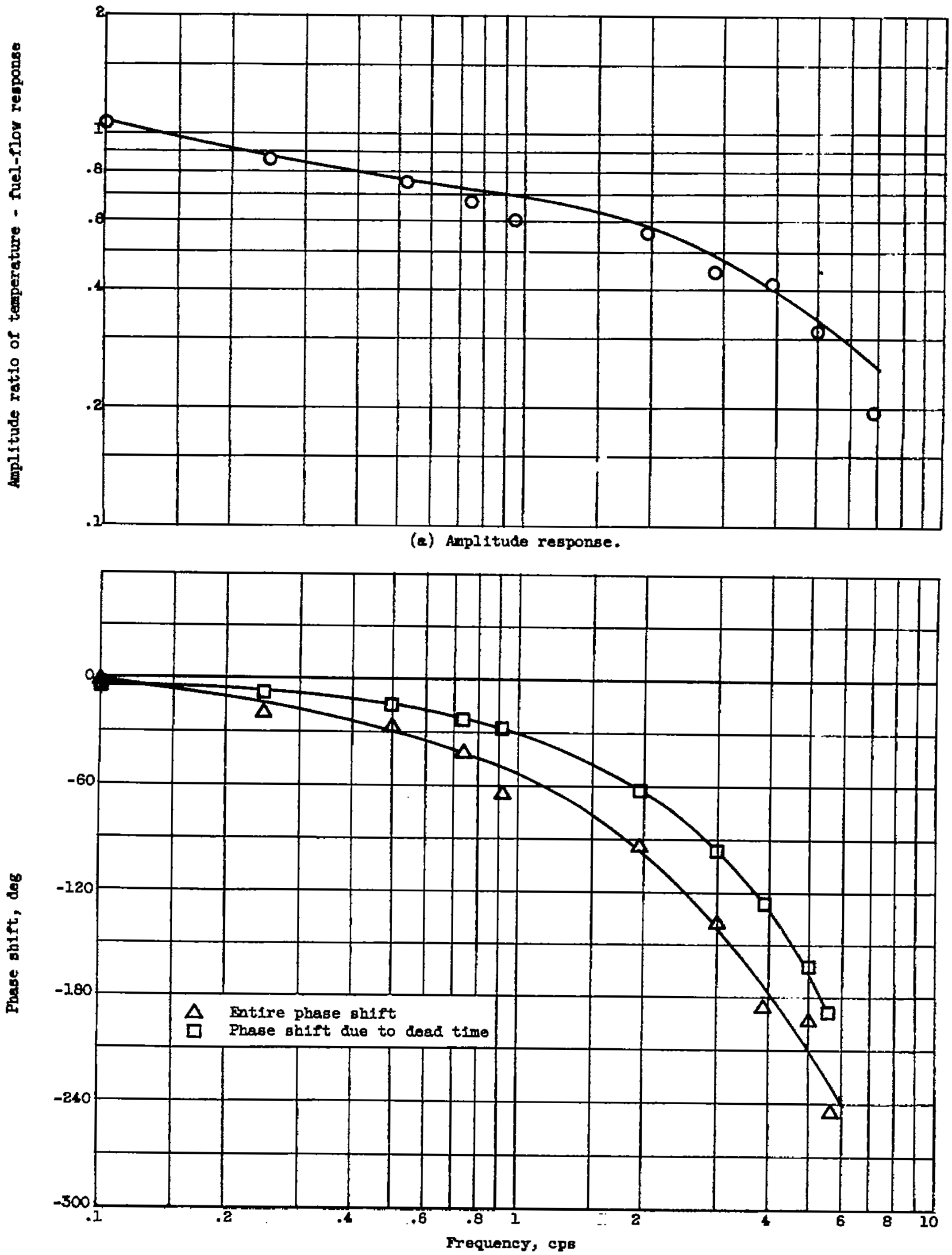

(a) Amplitude response.

(b) Phase-shift response.

Figure 4. - Frequency response of compensated temperature to fuel flow.

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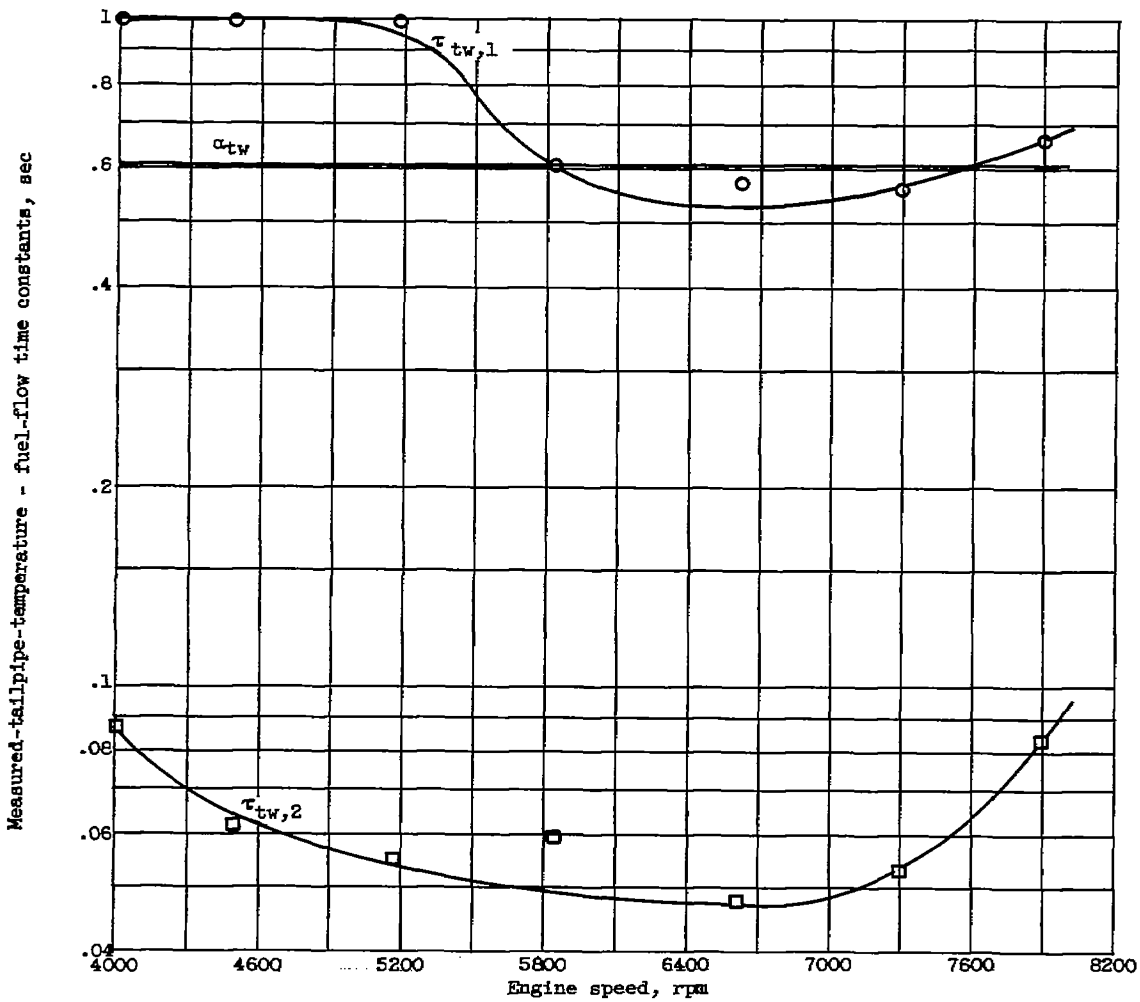

Figure 5. - Variation of measured-temperature - fuel-flow lag and lead time constants with engine speed.

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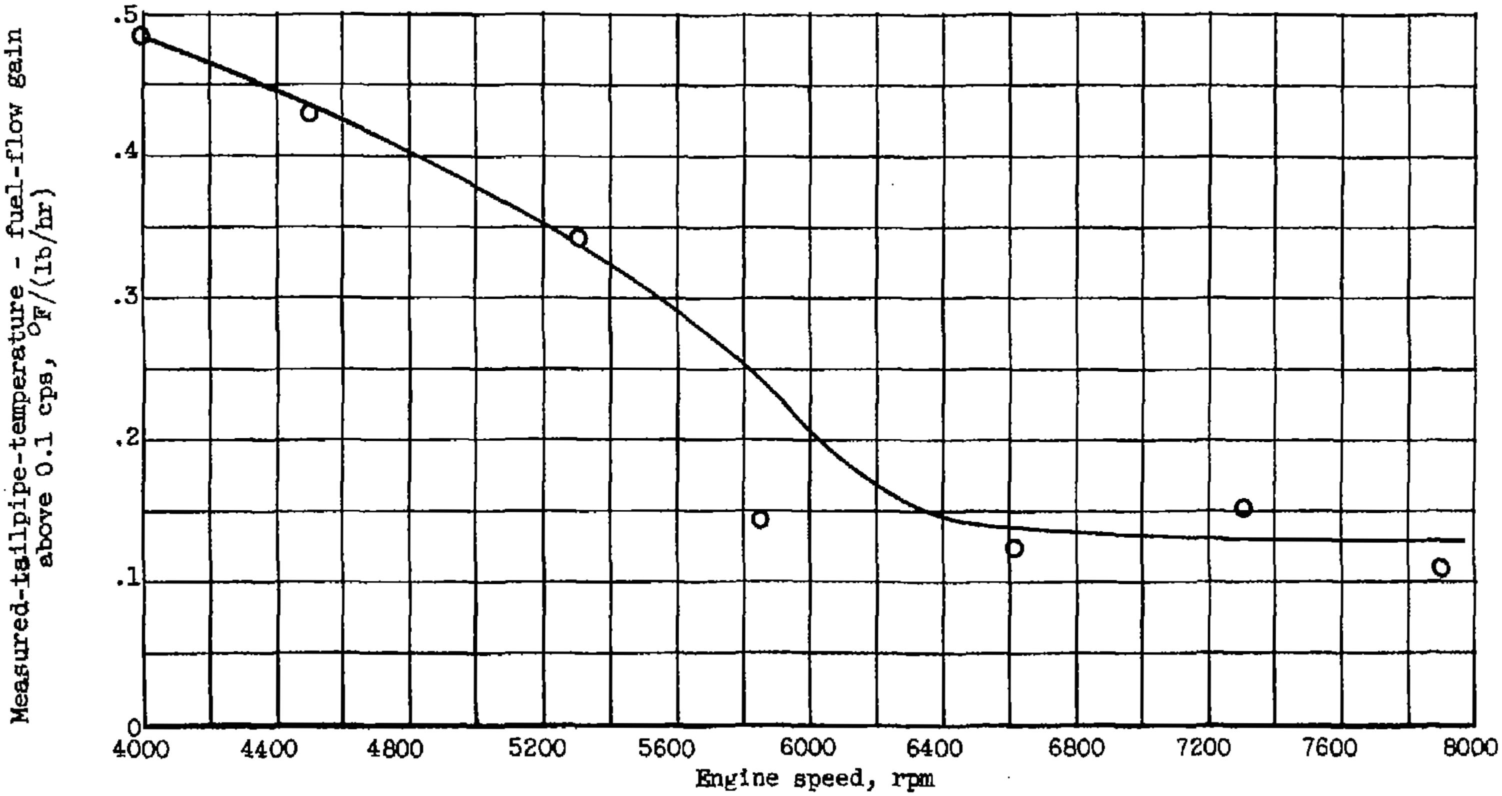

Figure 6. - Variation of measured-temperature - fuel-flow gain above 0.1 cycle per second with speed.

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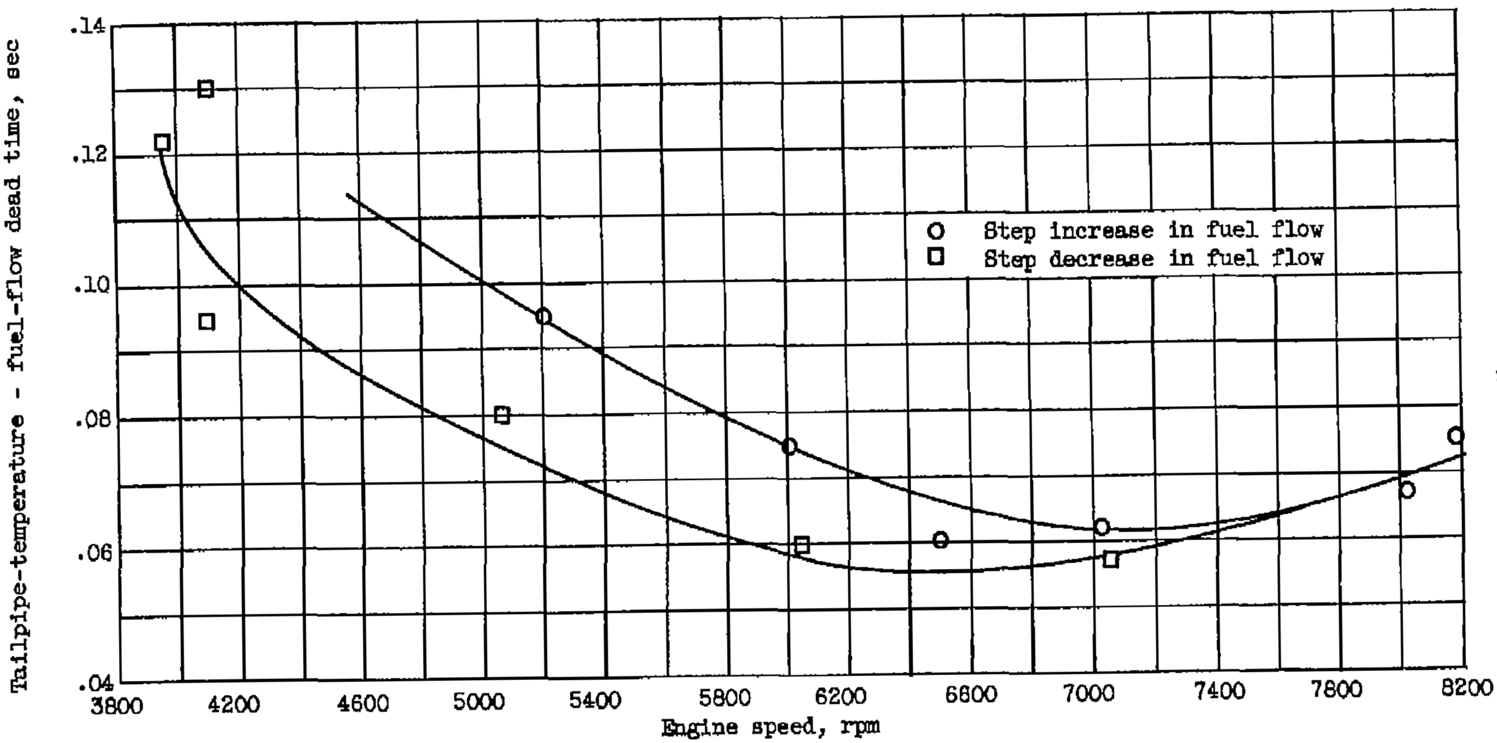

Figure 7. - Variation of temperature - fuel-flow dead time with speed.

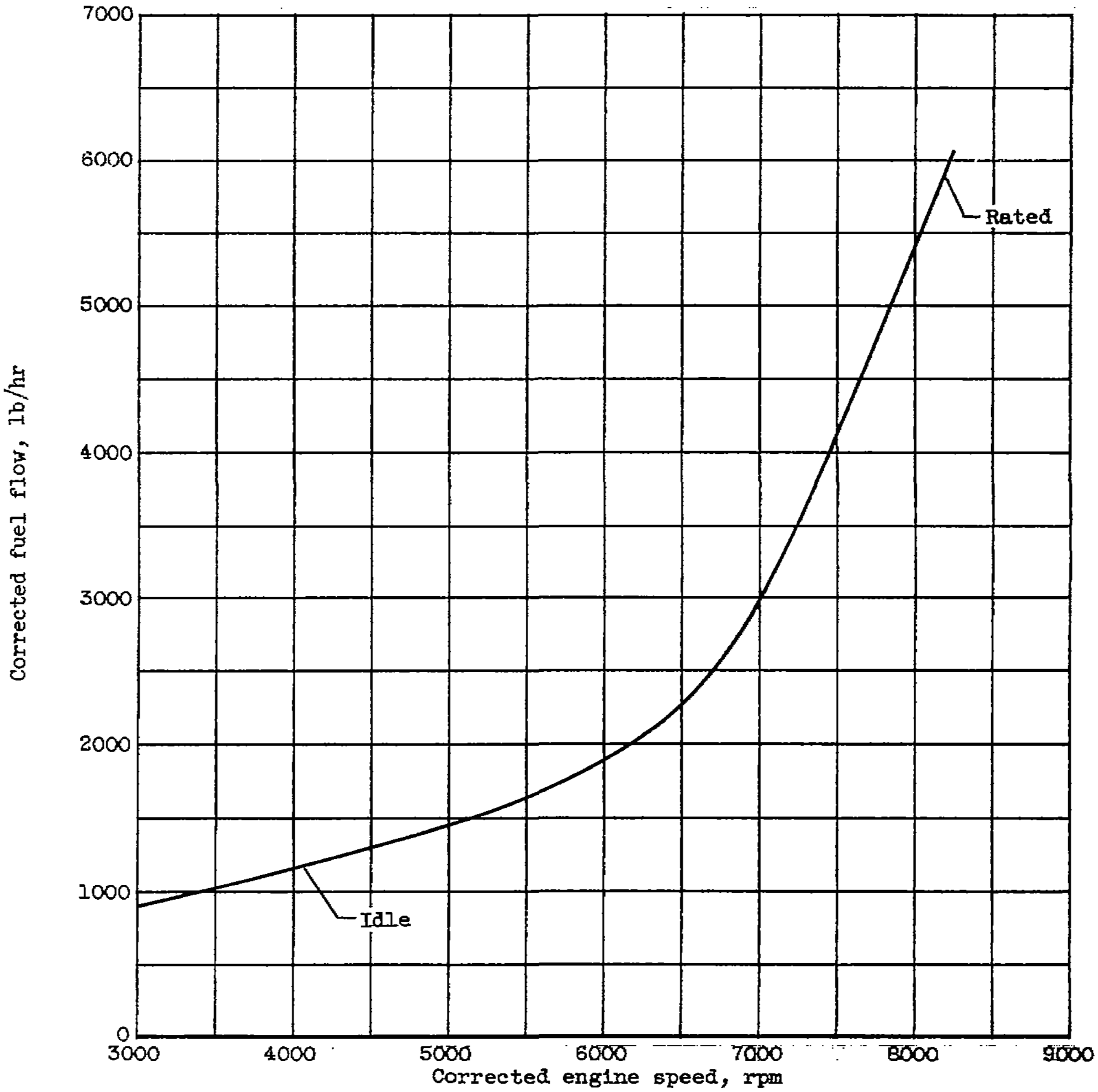

Figure 8. - Variation of steady-state fuel flow with corrected engine speed.

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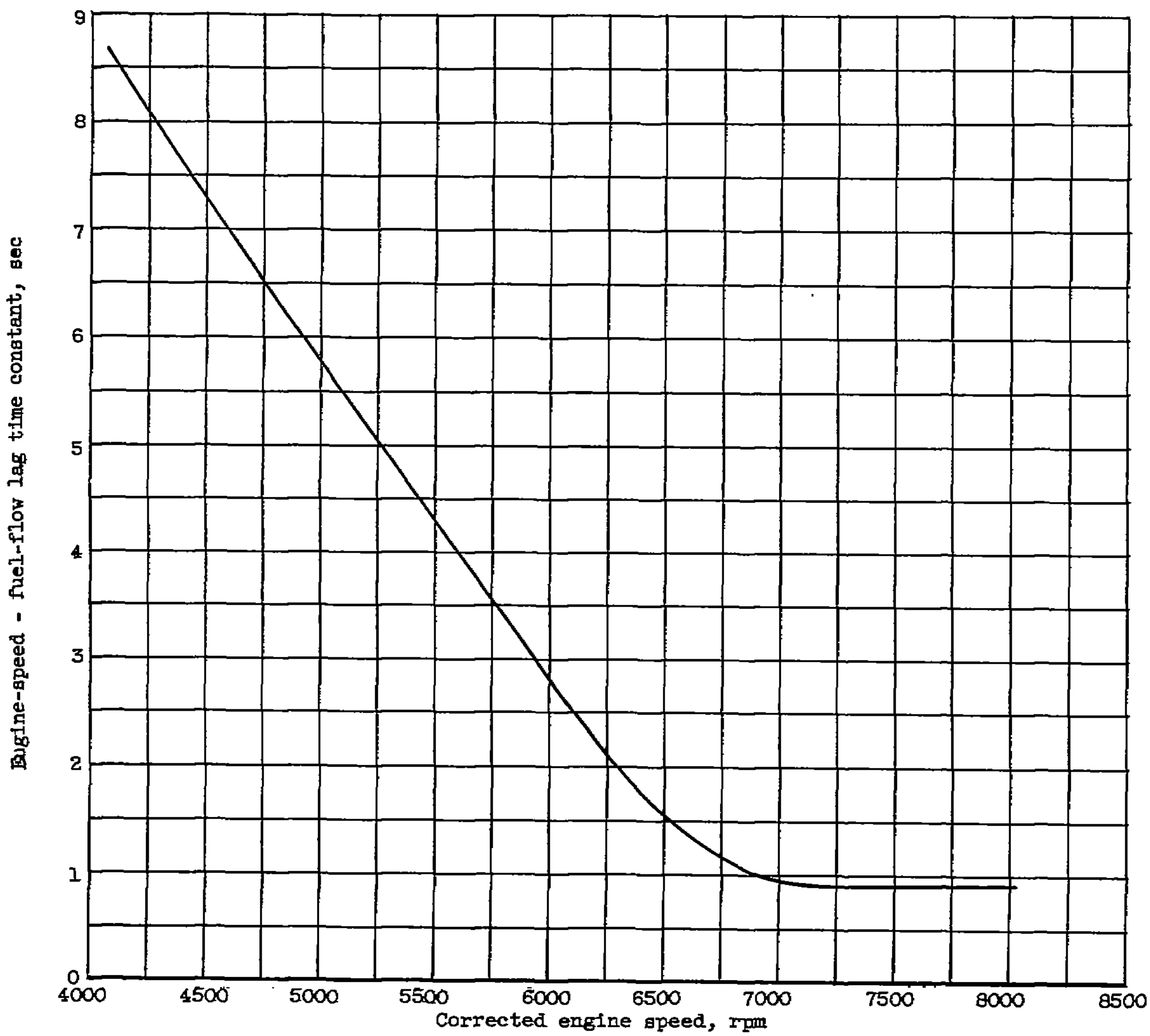

Figure 9. - Variation of speed - fuel-flow lag time constant with corrected engine speed.

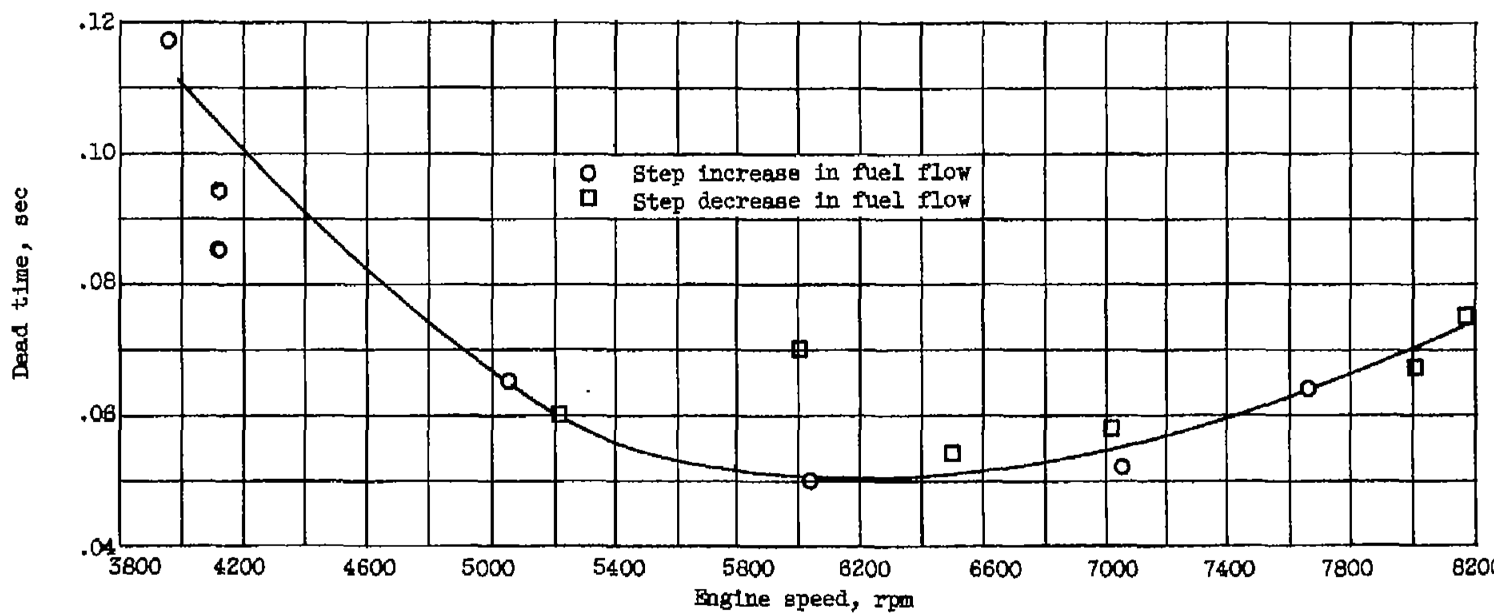

Figure 10. - Variation of speed - fuel-flow dead time with engine speed.

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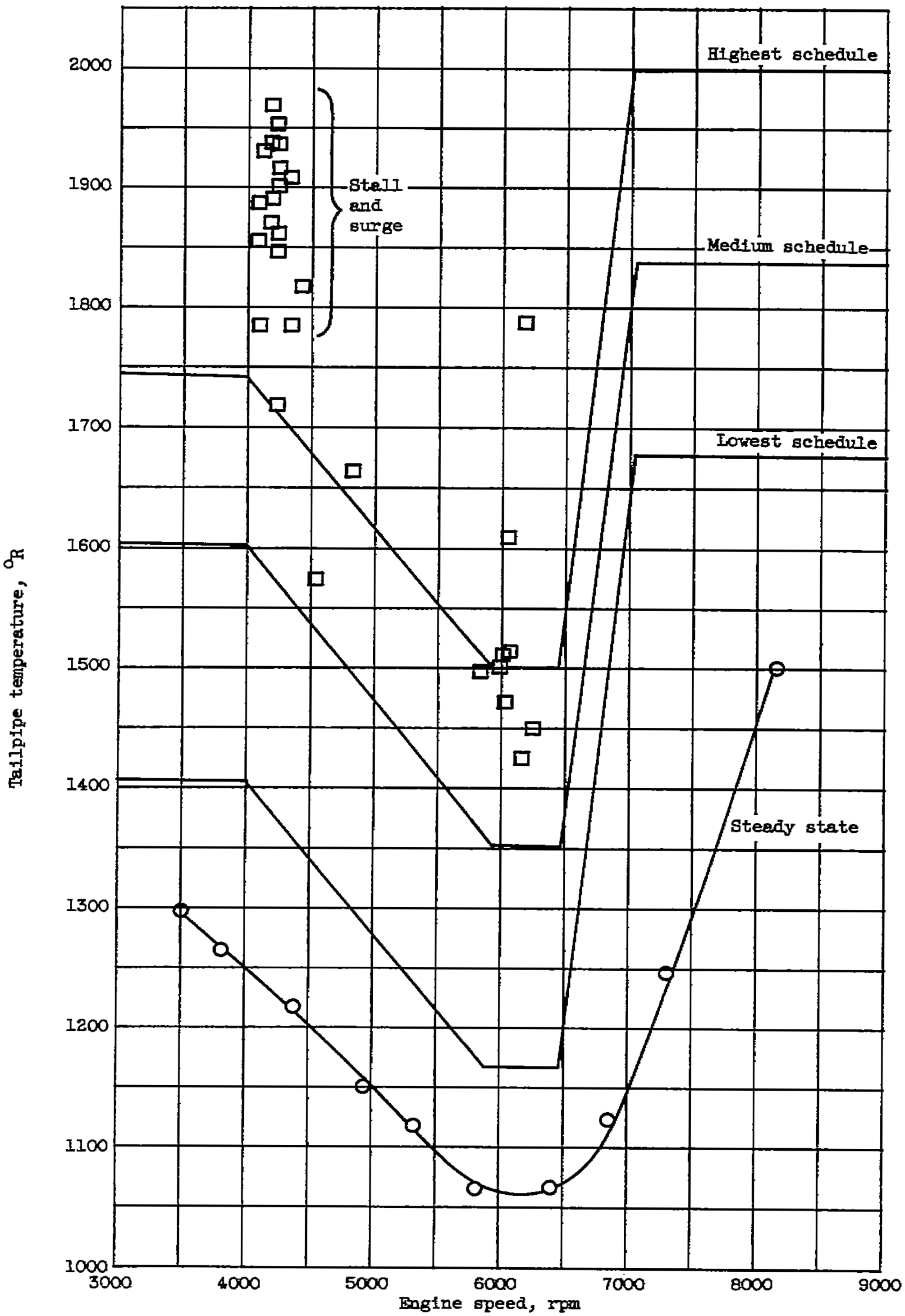

Figure 11. - Variation of stall, surge, scheduled, and steady-state temperatures with engine speed.

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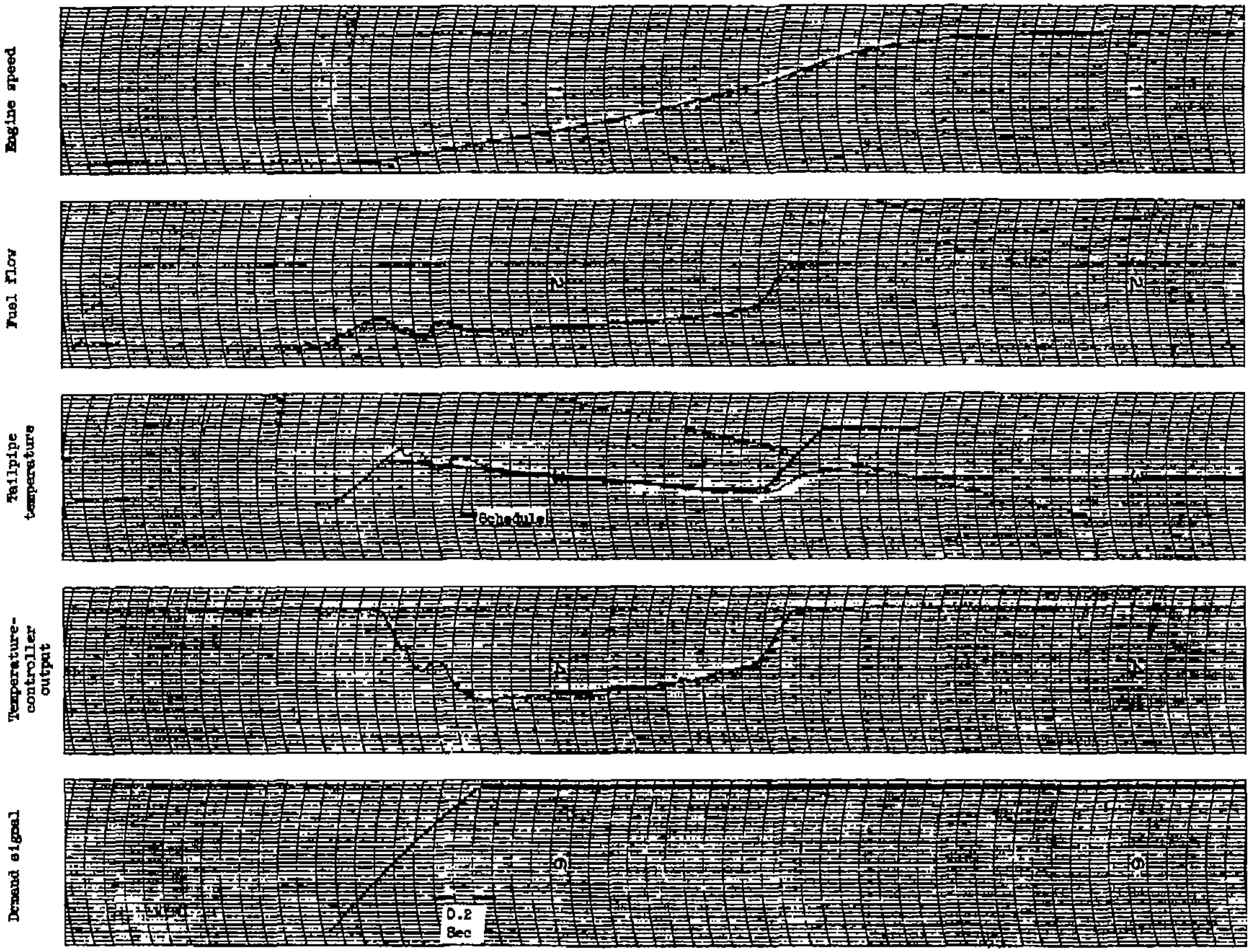

Figure 12. - Trace for typical acceleration using one-loop control.

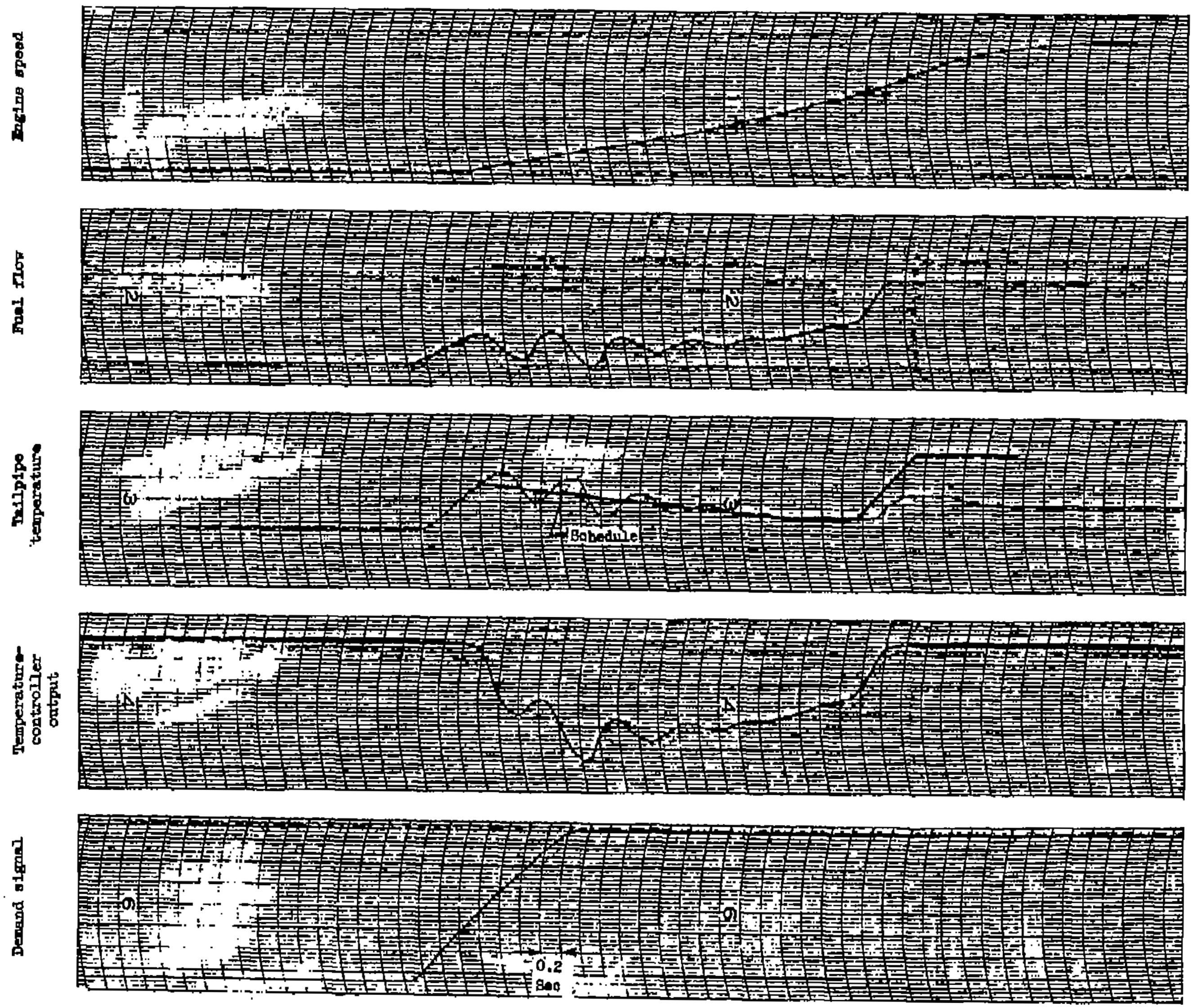

Figure 13. - Trace for acceleration with unstable one-loop control.

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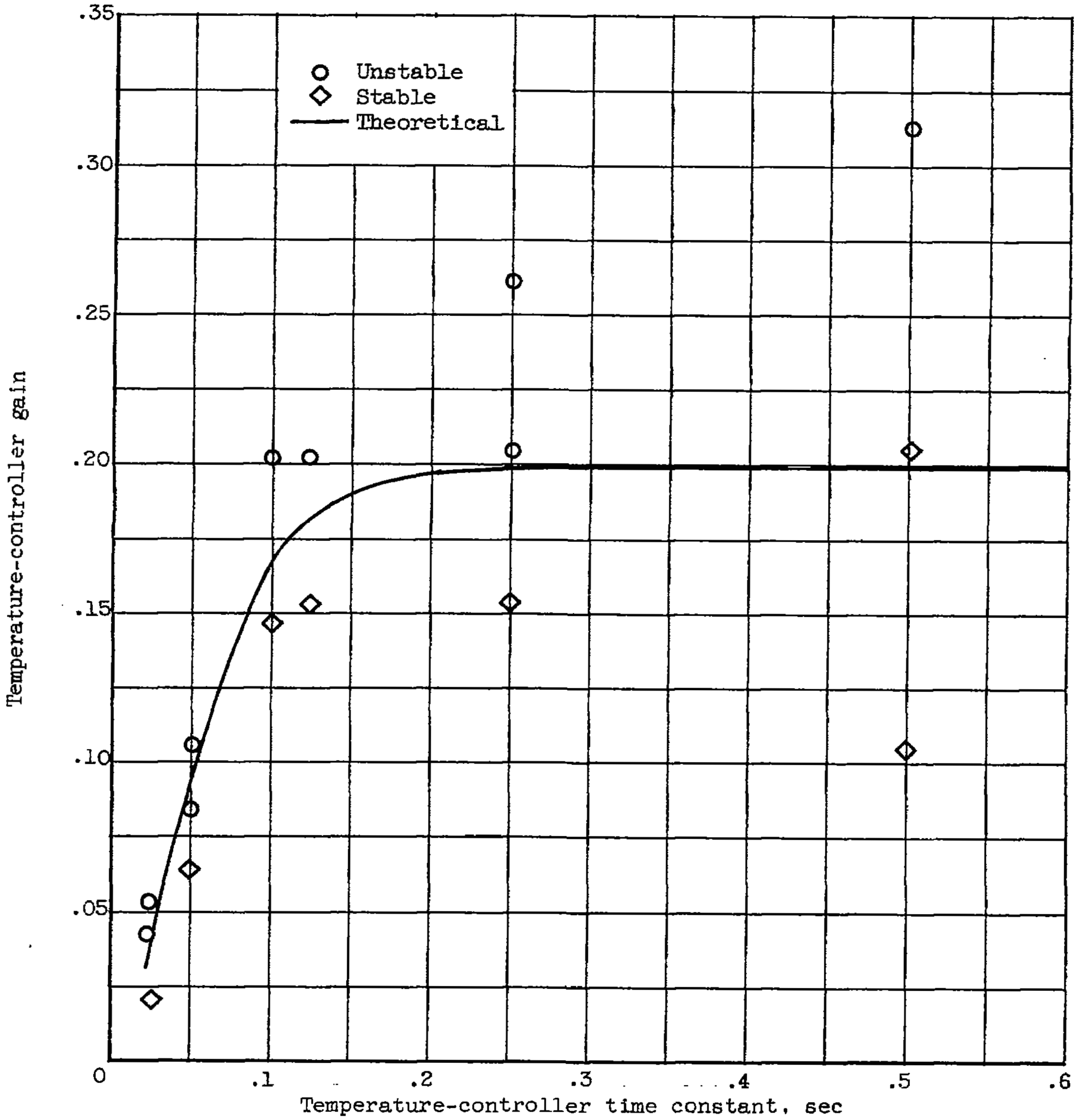
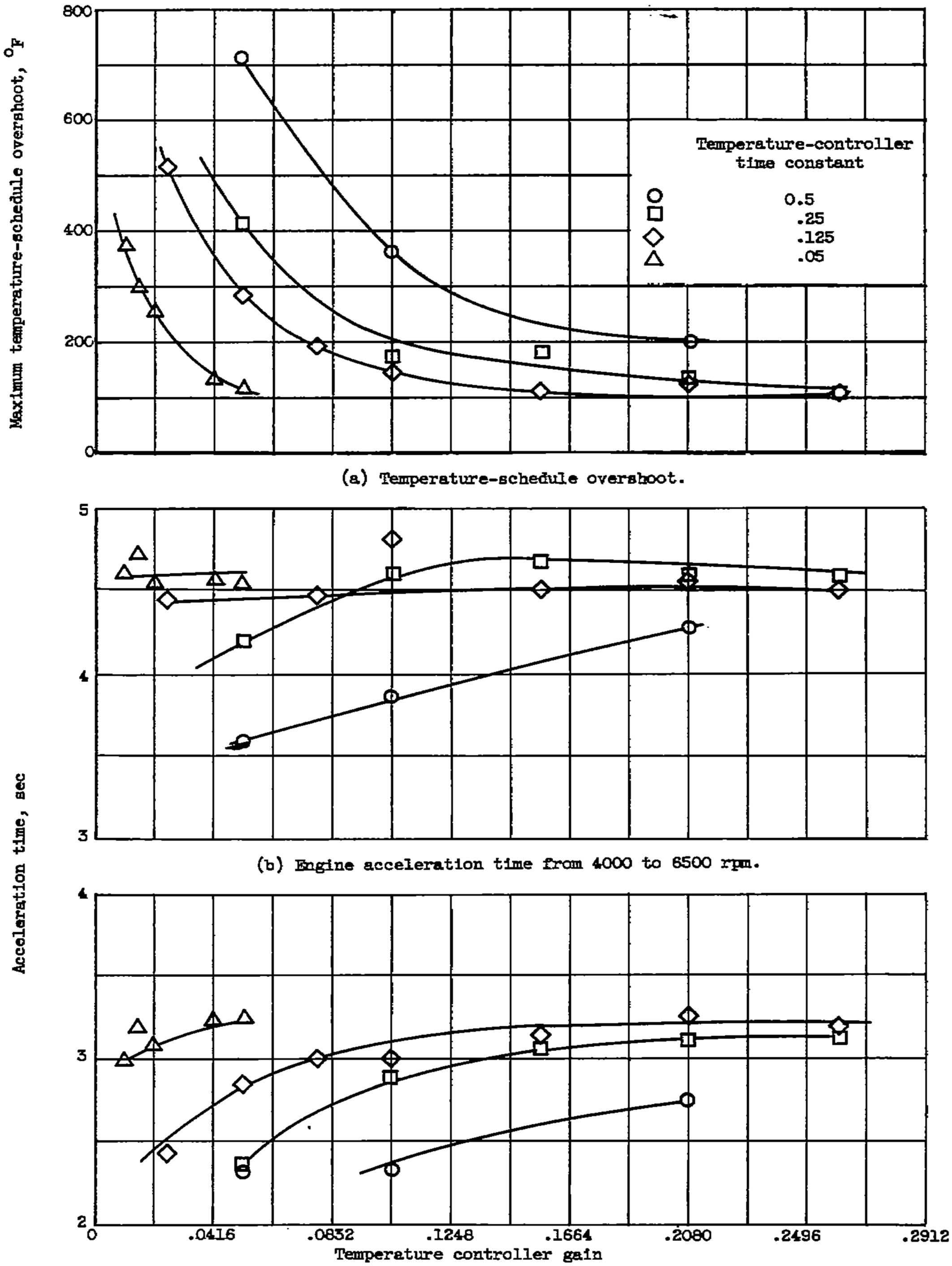


Figure 14. - Variation of experimental and theoretical temperature controller gain with controller time constant for stability.



(c) Engine acceleration time from 4000 to 5500 rpm.

Figure 15. - Variation of schedule overshoot and acceleration time with controller gain and time constant.

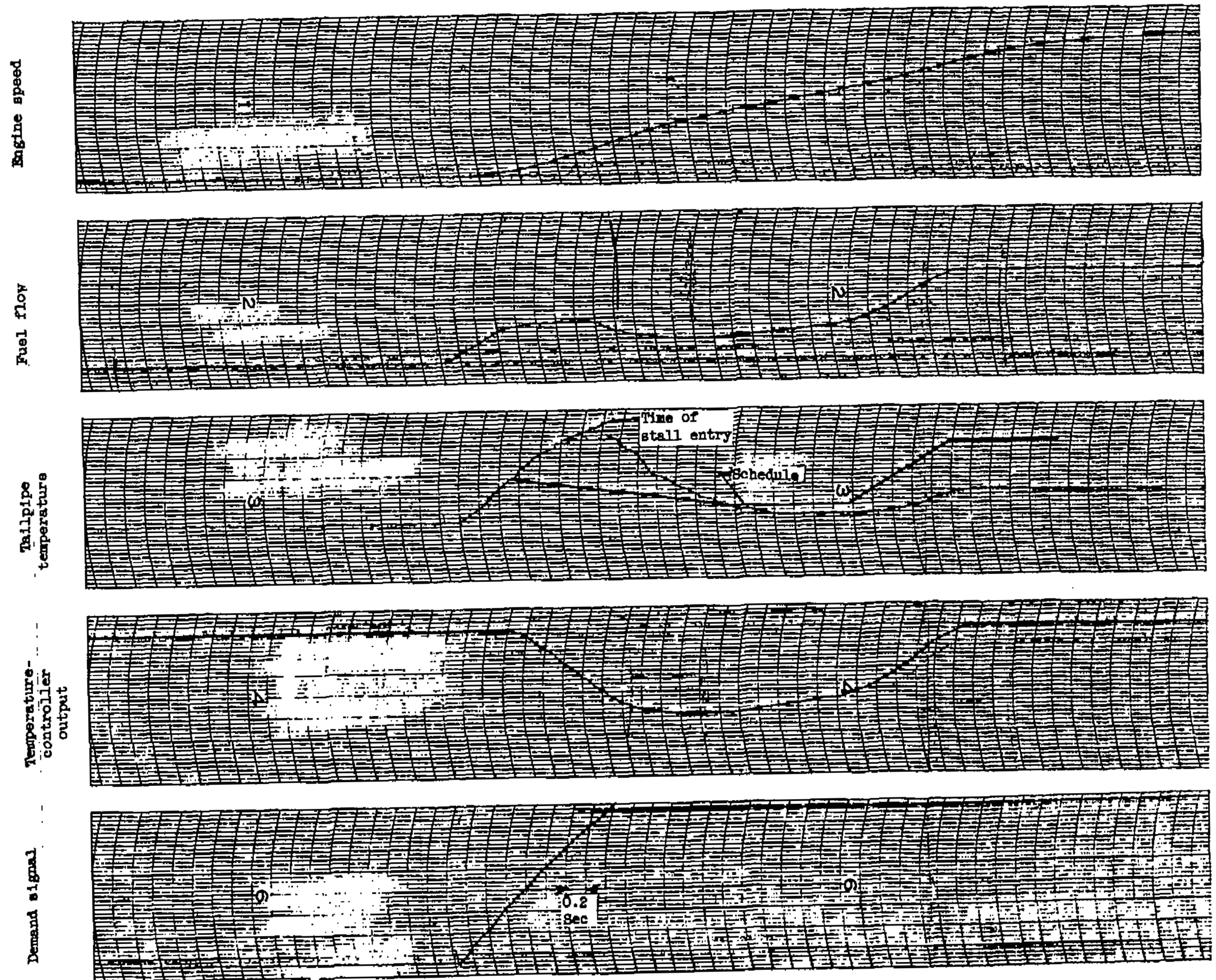


Figure 16. - Trace for acceleration with low controller gain and high controller time constant, which resulted in stall.

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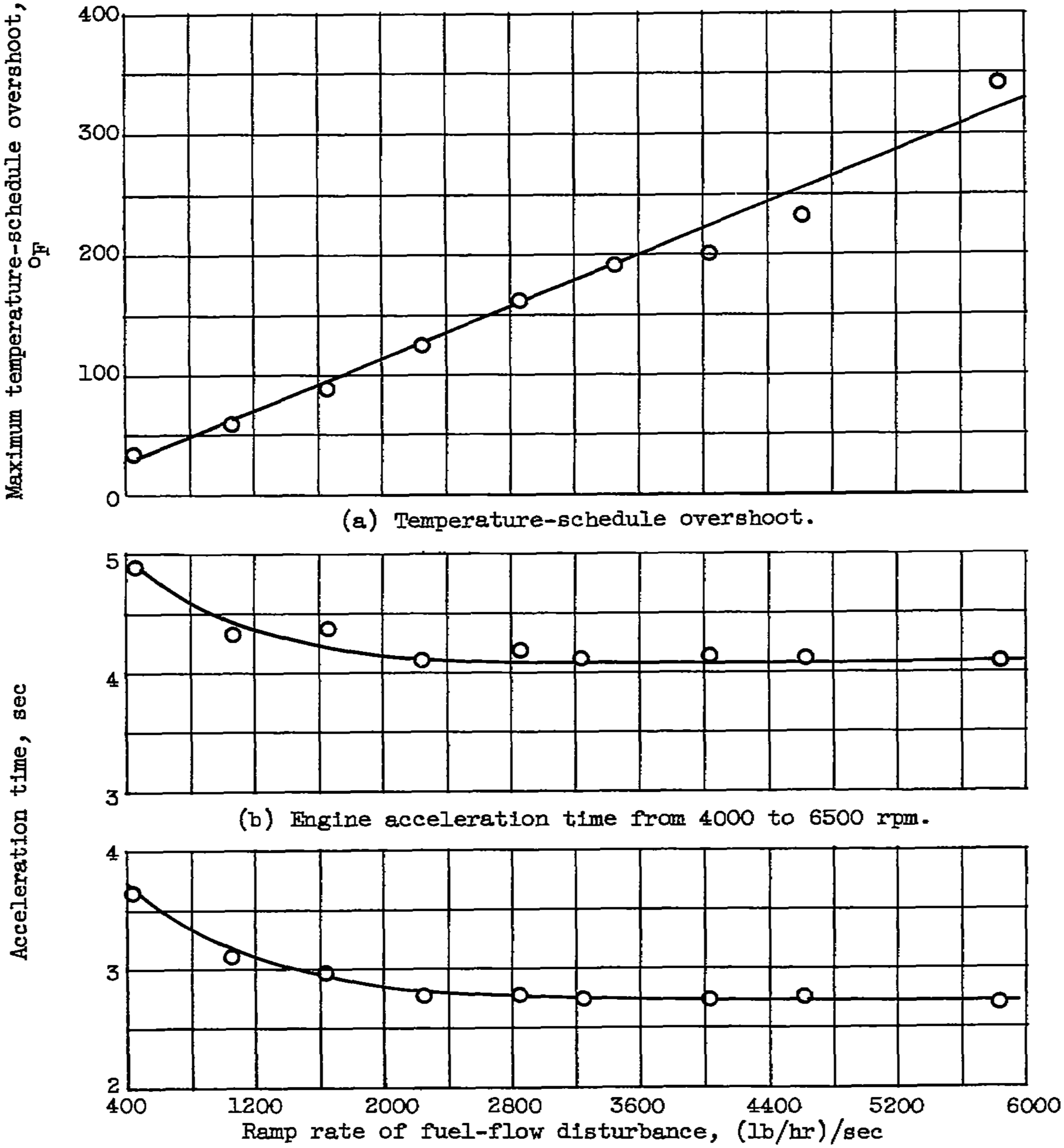
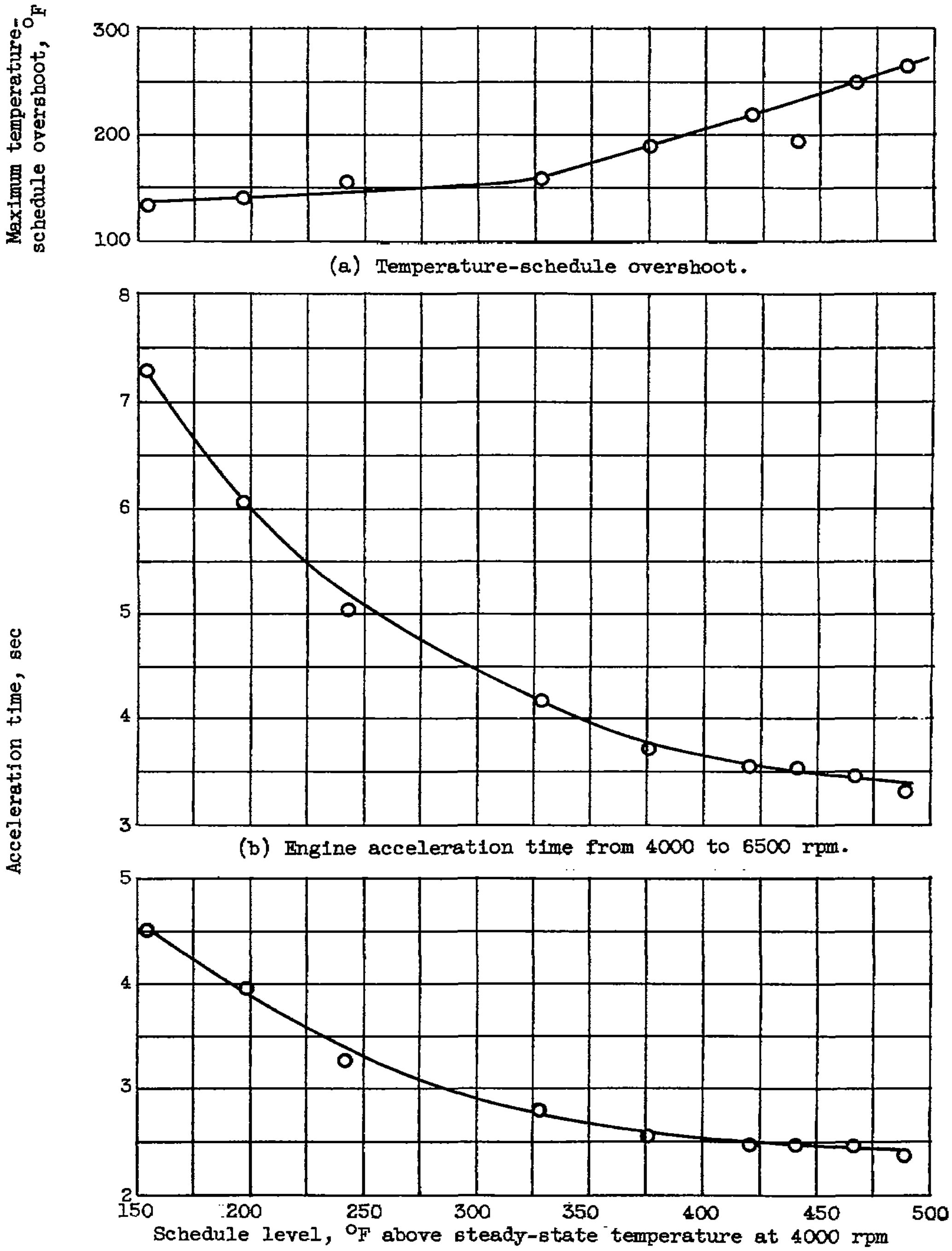


(a) Temperature-schedule overshoot.

(b) Engine acceleration time from 4000 to 6500 rpm.

(c) Engine acceleration time from 4000 to 5500 rpm.

Figure 17. - Variation of temperature-schedule overshoot and acceleration time with ramp rate of disturbance. Temperature-controller gain, 0.208; temperature controller time constant, 0.25; schedule level, 330° F above steady-state temperature at 4000 rpm.



(c) Engine acceleration time from 4000 to 5500 rpm.

Figure 18. - Variation of temperature-schedule overshoot and acceleration time with schedule level. Temperature controller gain, 0.208; temperature-controller time constant, 0.25; ramp rate, 2840 pounds per hour per second.

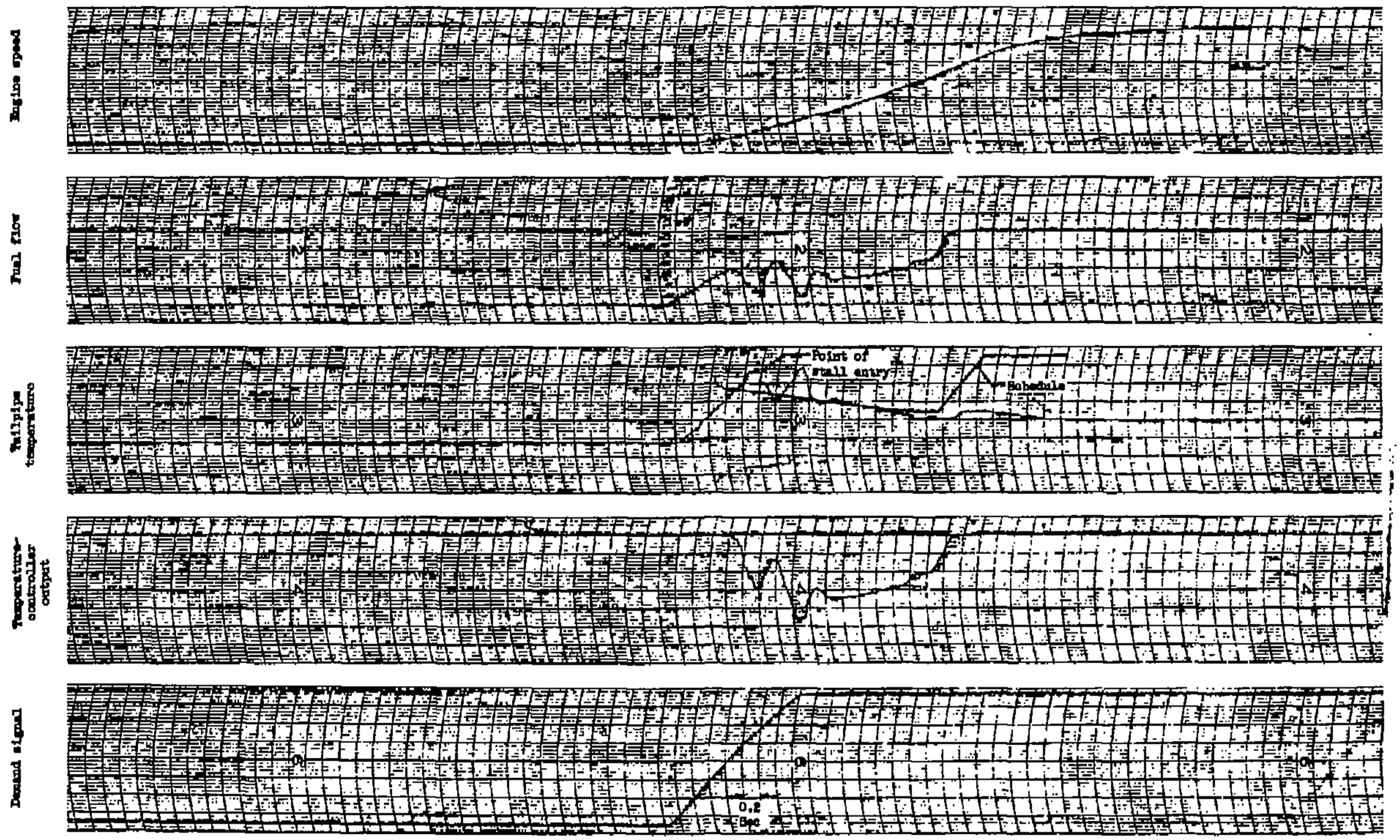


Figure 19. - Trace for acceleration with high schedule level that resulted in stall.

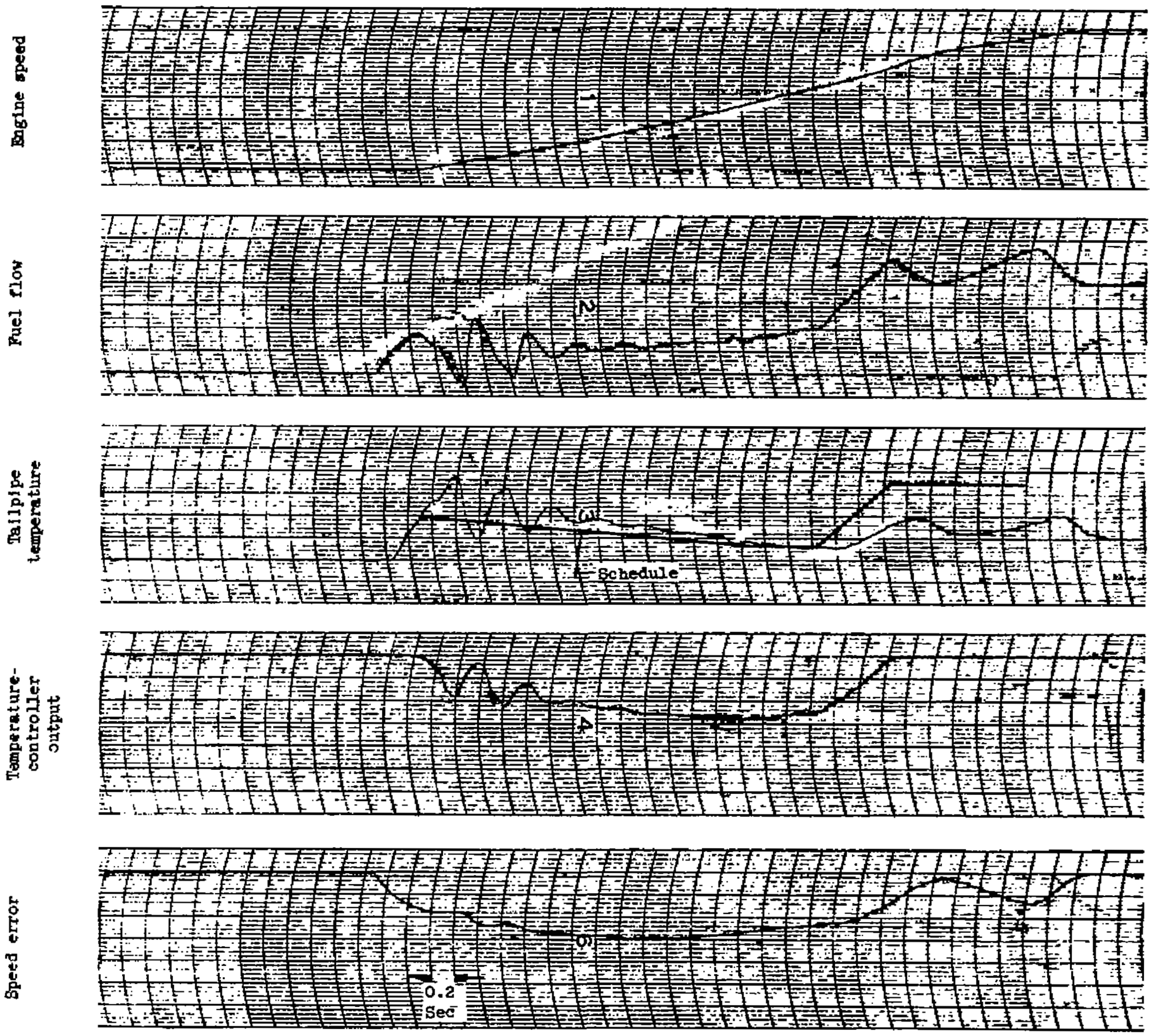


Figure 20. - Trace for acceleration with unstable two-loop control.

[redacted]

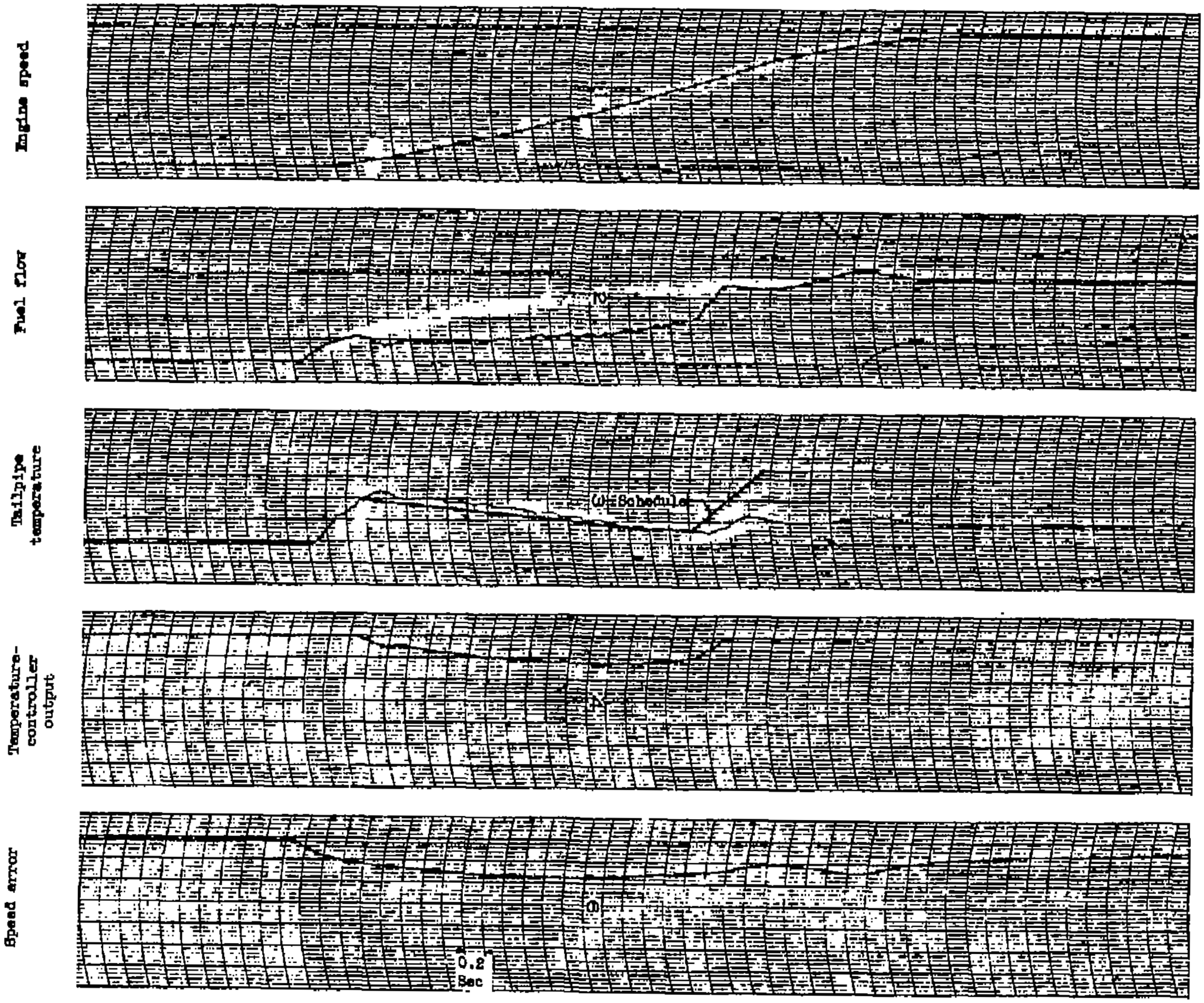


Figure 21. - Trace for acceleration with stable two-loop control.

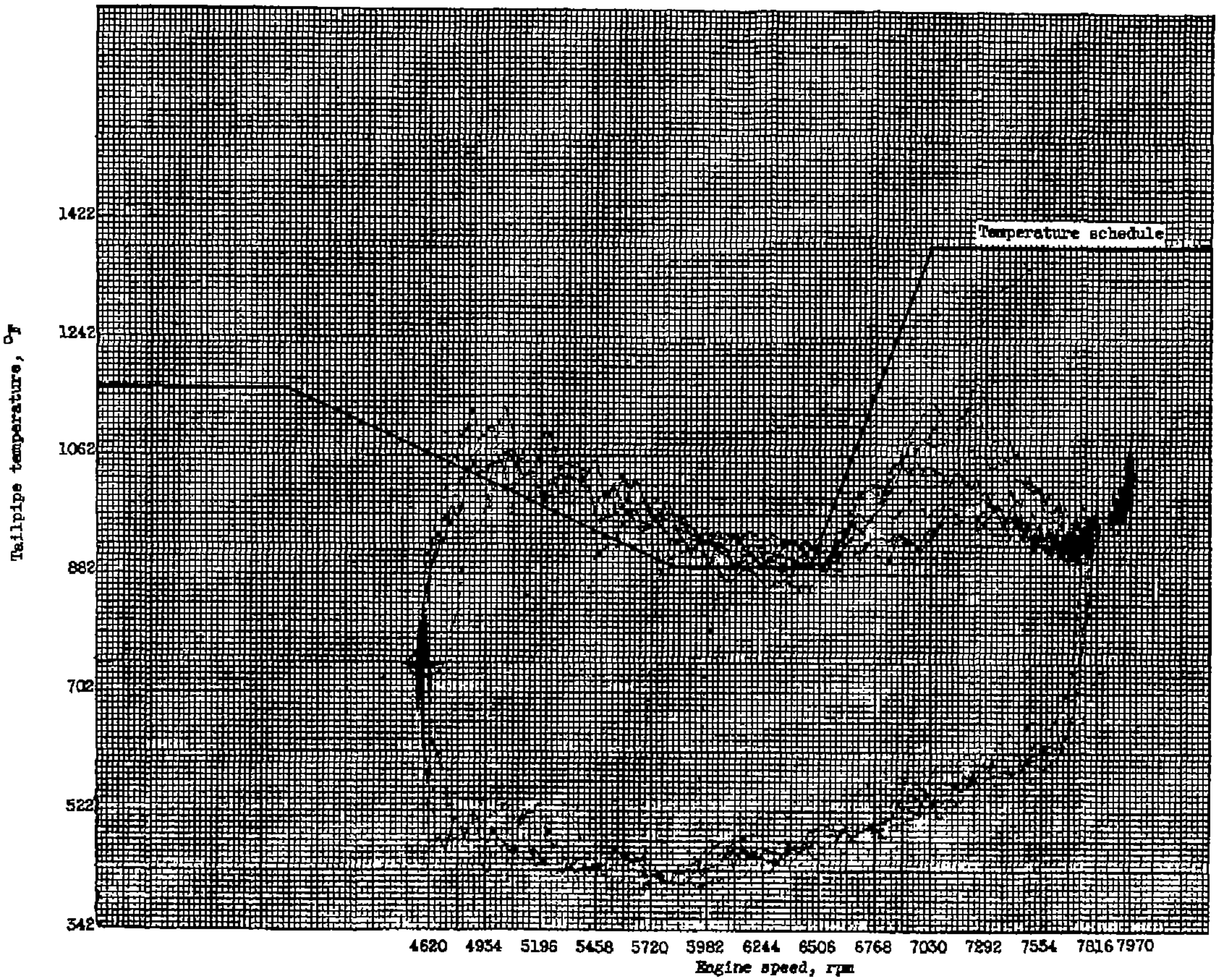


Figure 22. - Temperature variation with speed during repeated accelerations and decelerations ("go-around").

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