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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF AN OVERRIDING CONTROL TO EFFECT RECOVERY FROM SURGE AND STALL IN A TURBOJET ENGINE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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EXPERIMENTAL INVESTIGATION OF AN OVERRIDING CONTROL TO EFFECT RECOVERY FROM SURGE AND STALL IN A TURBOJET ENGINE

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SUMMARY

A manufacturer's standard fuel control for a turbojet engine was equipped with an experimental overriding system which would take corrective action in the event of compressor surge or stall. The override was designed to reduce engine fuel flow quickly to allow the engine to recover from surge or stall and then increase fuel flow at a slower rate to avoid repeated surge or stall and to successfully complete the acceleration.

Either of two engine parameters was used to operate the override system, tailpipe temperature or the derivative of compressor-discharge pressure. Using tailpipe temperature the override operated very well. After the control gains were properly set, surge and stall recoveries were effected and the number of stalls and surges limited. It was possible to accelerate the engine considerably faster using a rich accelerating schedule and the overriding system than by using the standard fuel control adjusted for a margin of safety, even though surge and stall were encountered. If the override using tailpipe temperature would fail to recover from stall or surge, engine temperature would be limited to some preset level.

The derivative of compressor-discharge pressure was then employed to operate the override. This system did not successfully combat stall, but was successful in recovering the engine from surge. A pressure sensor with a broader frequency response would have improved the override control operation when stall was encountered.

INTRODUCTION

Control systems for turbojet engines must contain some provision for dealing with compressor stall and surge. When these undesirable regions of engine operation are encountered, severe pressure pulsations and dangerously high engine temperatures may occur. If the engine is allowed to operate for an extended period in a surge or stall condition without the control system or the pilot taking corrective action to lower the temperatures, engine failure results.

Present-day turbojet controls employ various methods of dealing with the stall and surge problem. Some control systems incorporate a temperature override which reduces fuel flow in the event engine temperature exceeds some preset limit. Though an override such as this might limit engine temperature, and hence reduce engine damage, it is not intended to bring about a recovery from stall or surge, but relies on the pilot to detect these conditions and take corrective action. When stall or surge is encountered the pilot must detect the condition, reduce fuel flow to effect a recovery, and attempt the acceleration a second time. An unsuccessful acceleration could prove quite dangerous, especially during a wave-off from a landing attempt. Also, since temperature overrides are slow acting because of sensor dynamics, a finite time in an overtemperature condition must be tolerated before corrective action is taken.

Some turbojet controls use compressor-discharge pressure to detect stall and surge. By sensing compressor-discharge pressure and comparing it to a complex schedule, the control detects stall and surge when the value of sensed pressure is less than that of the schedule. A signal is then available to operate on fuel flow. Pressure systems are faster acting than existing temperature overrides but must rely on complex schedules for successful operation. The signal produced by the pressure system when stall or surge is detected is obtained rapidly enough so that by reducing fuel flow the proper amount, the engine recovers from these conditions. However, when the engine does recover, compressor-discharge pressure rises and the control, sensing the recovery, allows fuel flow to return to its initial value. Repeated stalls or surges then occur, usually resulting in an unsuccessful acceleration. The pilot must be called upon to reduce fuel flow and re-attempt the acceleration.

Other turbojet controls contain no provision for taking corrective action when the engine encounters surge or stall, but use conservative accelerating schedules in attempting to avoid these conditions. This latter type control suffers from two major drawbacks. Because of the conservative schedule, the acceleration time is greatly increased, and thus the effectiveness of the control is reduced. Secondly, if for any reason, possibly inlet-air distortion or engine deterioration, stall or surge is encountered, the control takes no corrective action. Under these circumstances the engine is permitted to operate for extended periods in surge or stall.

The purpose of this investigation was to design and operate an override control to take corrective action against stall and surge in a turbojet engine. This system would detect stall and surge and immediately reduce fuel flow in order to effect a recovery, then increase fuel flow back to its initial value in a manner so as to avoid repeated surge or stall. A control such as this would ensure a successful acceleration even though surge or stall were encountered. The override control would detect stall and surge whether they occurred during transients or in steady-state operation as a result of inlet distortion or altitude effects.

A turbojet fuel control of the type which relies on a conservative schedule to avoid stall and surge was selected for the test. This control was equipped with the overriding system, which was designed to operate only when stall or surge was encountered. Two signals were used to detect stall and surge; the first was tailpipe temperature, and the second was the derivative of compressor-discharge pressure.

A previous NACA investigation (ref. 1) revealed a sharp rise in compensated tailpipe temperature at the onset of stall and surge. It was desired to use this sharp rise in temperature to bring the overriding system into action. A limiting temperature was incorporated into the override that would not be exceeded during normal engine operation. When surge or stall occurred, the sharp rise would drive engine temperature beyond the limiting temperature, thus providing a signal with which to operate on fuel flow.

For the second part of the program, the derivative of compressor-discharge pressure was used to detect stall and surge. This technique has previously been employed by the NACA (ref. 2) to detect surge in a different turbojet operated with an experimental control. When stall or surge occurs in a turbojet engine, compressor-discharge pressure exhibits a sharp drop. The derivative of this parameter with respect to time would show a large negative value at the onset of stall or surge. This large negative value was used to detect stall and surge for the overriding system.

APPARATUS

Control System

The axial-flow turbojet chosen for the investigation, along with the standard fuel control and pump supplied with the engine, was installed in an NACA altitude facility. A block diagram of the control system is shown in figure 1. A bypass line containing a fast-acting servo valve was installed around the standard fuel control and pump. Overriding action on the standard fuel control was obtained by opening the servo valve, which allowed some of the fuel that had gone through the standard fuel control to be bypassed. The standard fuel control was a schedule-type control which regulated fuel flow according to engine speed. It relied on a conservative schedule to avoid stall and surge and contained no provisions for combating these conditions.

Either tailpipe temperature or the derivative of compressor-discharge pressure $\dot{P}$ was used to operate the override (fig. 1). Using tailpipe temperature, the standard fuel control was in complete charge whenever the engine operated stall- and surge-free. The electronic computer detected stall and surge by comparing the sensed temperature to a preset limiting value. The sharp rise in temperature occurring at the onset of stall or surge drove sensed temperature above the limiting value. When stall or surge was detected, the electronic computer sent a signal which caused the servo valve to open quickly. As long as the engine temperature remained above the limiting value, the computer reduced fuel flow further by opening the servo valve wider. When the engine recovered from stall or surge, the sensed temperature dropped below the preset limit and the computer closed the servo valve at a slow rate to avoid repeated stall or surge. When $\dot{P}$ was used to operate the override, the sequence of operation was the same as with tailpipe temperature.

A circuit diagram of the electronic computer and derivative network is shown in figure 2. The switch selected the parameter to operate the override.

The temperature sensor compensator compensated for first-order sensor dynamics, which resulted in a fast-responding temperature signal. Thermocouple compensation similar to that employed is discussed in reference 3. In the electronic computer circuit, amplifier 3 shaped the signal which opened and closed the servo valve, and diode 1 and the resistor R_6 altered the signal so that the valve opened quickly and closed at a slower rate. (Symbols are defined in appendix A.) Detailed explanations of the circuits shown in figure 2, including their transfer functions, appear in appendix B.

Instrumentation

Engine speed, tailpipe temperature, fuel flow, compressor-discharge pressure, and servo-valve position were recorded. Engine speed was measured by means of a tachometer generator and its frequency response was not obtained.

Tailpipe temperature was sensed by 14-gauge thermocouples. The thermocouple output was then passed through a compensating network which canceled the first-order dynamics of the thermocouples. The temperature sensing circuit did not seem to attenuate the 5-cps surge frequency.

Fuel flow was sensed by a turbine-type flowmeter. This device also seemed to have a flat frequency response in the surge frequency region.

Compressor-discharge pressure was sensed by a strain-gage transducer and did attenuate the surge frequencies. Rotating stall frequencies of the order of 50 to 100 cps were completely filtered out.

Servo-valve position was sensed by a differential transformer mounted on the valve. The frequency response of the servo valve is essentially flat to beyond 20 cps.

PROCEDURE

Desired flight conditions of altitude and Mach number were set in the altitude chamber. Normal engine transients were run to establish the operation and accelerating times of the standard fuel control system. The speed - fuel-flow accelerating schedule of the standard fuel control was then enriched up to and beyond the stall and surge lines and action of the override was recorded.

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RESULTS AND DISCUSSION

A record of a transient taken as part of another program is presented as figure 3. The turbojet and fuel control used to obtain the data in figure 3 are of the same type and model as those chosen for the override investigation. In the run of figure 3, the engine encountered stall at 3.3 seconds. Since this fuel control contains no provision for combating stall and surge, the engine was allowed to operate in this condition for over 15 seconds. A turbine failure resulted from the transient, probably occurring at about 18.5 seconds. The slow-responding temperature sensor used for tailpipe temperature did not reveal the sharp rise in temperature at the point of stall.

Distinctions between surge and stall are important in control and can be made by reference to figure 3. Cycles of surge appear at 2.8 and 3.3 seconds. A large variation in pressure occurs during the surge cycle and the frequency is low (about 5 cps). This surge is sufficiently violent to excite the entire aircraft, and thus the pilot is aware of surge.

Stall occurred after 3.6 seconds and persisted up to failure at 19 seconds. The frequency is much higher than for surge (about 50 to 100 cps), and its amplitude is low. Consequently the engine might be in stall, and the pilot might not be aware of this condition and the accompanying destructive temperature.

The engine and fuel control selected for the override test, the same models as used for figure 3, were modified by the manufacturer to allow the engine to operate farther from its stall and surge lines. These changes considerably increased accelerating times. Figure 4 shows a normal transient of the test engine from 81 to 101 percent rated speed at a flight altitude of 45,000 feet and a Mach number of 0.68. The acceleration required 17 seconds. Values given on all figures have not been corrected to inlet conditions but are actual readings.

The accelerating schedule of the standard fuel control was then enriched as far as possible without encountering stall or surge. Figure 5 shows such a run. By setting the limiting temperature to be used in the override to a value above the maximum encountered in figure 5, the override would not be brought into action during normal engine operation.

The transient of figure 5 covered a wider speed range than figure 4, but accelerating time was reduced to 6.4 seconds. Rated tailpipe temperature is also shown on figure 5, and dead time is discussed later.

Operation of Override Using Tailpipe Temperature Signal

Enriching the accelerating schedule further and using the limiting temperature from figure 5, the override was operated using tailpipe temperature. Figure 6 shows an acceleration where the override recovered the engine from surge five times and from stall twice, and still completed a larger acceleration 1.6 seconds faster than in figure 4. The tailpipe temperature trace on figure 6 clearly shows the sharp rise to a high temperature occurring at the onset of stall and surge. Control gains in the electronic computer (fig. 1) were not set correctly when the transient of figure 6 was run. The servo valve closed too rapidly after stall and surge recovery, resulting in repeated stalls and surges. The high gain setting also caused the servo valve to limit at its open position.

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Gain in the computer was reduced to enable the servo valve to follow the temperature error more accurately and the computer was reset to close the servo valve more slowly. Figure 7 is a transient run with these new override settings. In figure 7 surge was encountered twice and stall once. No limiting occurred on the servo valve and the acceleration was completed in about 11 seconds. Figures 5 and 7 are examples of how a control system equipped with the temperature override could be set up to operate. The accelerating schedule of the fuel control could be set to provide rapid accelerations (fig. 5); then if stall or surge were encountered, the override would ensure successful accelerations requiring somewhat longer times (fig. 7).

Demonstration of the override control at the flight conditions under which engine failure occurred was considered desirable. Inlet conditions were set to correspond to those where the turbine failure shown in figure 3 was experienced, an altitude of 35,000 feet, and a flight Mach number of 0.54. A transient was run to record the operation of the standard fuel control under these conditions and is presented as figure 8. The standard fuel control operating on its normal accelerating schedule required almost 10 seconds to accelerate the engine from 83 to 101 percent rated speed.

With all other conditions the same, the fuel flow schedule was enriched beyond the stall line. Figure 9 shows a transient run using this rich schedule. After the start of the transient of figure 9, engine speed had increased rapidly for 2.3 seconds when stall was encountered. In the run of figure 3, where stall also was encountered, the control allowed the engine to operate in stall for an extended period which resulted in a turbine failure. With the rich schedule (fig. 9), however, the override recovered the engine from stall within 0.5 second and successfully completed the acceleration in 6.0 seconds.

The limiting temperature used for the transient shown in figure 9 was about 1600° F. This is 40° lower than that used in the transients of figures 6 and 7. The higher temperature would have been more desirable for the figure 9 transient because the 1600° F value was exceeded while the engine was accelerating normally (after 4.8 seconds). Over the range of altitudes and engine speeds covered during the investigation, it appeared that a constant limiting temperature of 1640° F could have been used. However, on different turbojet engines operated over wider ranges of flight conditions and engine speeds, a limiting temperature that varies with flight conditions or engine speed may be necessary.

If the override fails to recover the engine from stall or surge, engine temperature will be held to the preset limit. Figure 10 shows stall occurring during a transient where the computer gain was too low to reduce fuel flow sufficiently. After the engine failed to recover from stall the override held temperature to its preset limit until at 9.4 seconds the engine operator reduced fuel flow manually. The limiting temperature used for figure 10 was 165° F above rated tailpipe temperature. If the override control were installed in an airplane and its corrective action were unsuccessful, just as it was in the transient of figure 10, the pilot would be called upon to recover the engine and re-attempt the acceleration but engine temperature would be limited. Though the limiting temperature is above rated, it would be less harmful to the turbine blades than the prolonged 2300° F temperature encountered during the transient of figure 3.

Dead time that exists in a turbojet engine between temperature and fuel flow could hinder the operation of the override using the temperature signal. In figure 5, which shows a normal engine transient, a delay of about 0.15 second can be seen between the time fuel flow is reduced and its effect is felt in tailpipe temperature. Figure 11 shows a transient encountering surge at 50,000 feet with the override inoperative. A dead time of 0.30 second is detectable. In figure 6, a dead time of 0.20 second can be seen after the engine encountered stall. The presence of this dead time means that even though stall was detected and fuel flow reduced immediately, the effect of the reduction would be delayed by the magnitude of the dead time. Overtemperature operation for a fraction of a second would not be harmful to the engine, but it might make recovery from stall or surge more difficult. A previous investigation (ref. 4) disclosed that the hysteresis associated with stall recovery varies as some direct function of the length of time the engine operates in a stalled condition. The dead time must also be considered in the stability limit of the override control.

Operation of Override Using Derivative of Compressor-Discharge Pressure Signal

The temperature sensor was disconnected and the override was connected to operate on the derivative of compressor-discharge pressure $\dot{P}$. In the $\dot{P}$ circuit, the potentiometer (fig. 2) determined the negative value of $\dot{P}$ below which the override would come into play. It was necessary to set the potentiometer so that the override would not come into play during steady-state operation or from the negative $\dot{P}$ resulting from rapid fuel cutbacks, but only operate on the very large negative value occurring at the onset of stall and surge.

Although not successful in recovering the engine from stall, the $\dot{P}$ override as it was operated, was successful in recovering the engine from surge. As can be seen from figure 12, the engine encountered surge twice and both times the override's action effected a recovery after 2 cycles of surge. The low-frequency surge cycles were passed by the compressor-discharge sensor so that the servo valve was opened wider on each cycle.

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The override operating with $\dot{P}$ was not successful in recovering the engine from stall. Figure 12 shows that when stall was encountered after about 6.0 seconds, the control cutback fuel upon receiving the large negative $\dot{P}$ signal and then allowed fuel flow to increase back to its former level (7-second point) even though the engine remained in stall. At 7 seconds tailpipe temperature (fig. 12) reached a very high value and remained at this dangerous level until fuel flow was reduced manually about 1 second later. If fuel flow were not reduced manually, turbine failure could have occurred.

The $\dot{P}$ override may have been successful in recovering the engine from stall had a sensor with a broader frequency response been used to measure compressor-discharge pressure. Reference 4 shows that a 50- to 100-cps frequency can be detected when the engine operates in a stalled condition. Examination of the compressor-discharge pressure trace of figure 12 in the 6- to 8-second region shows that no such frequency was passed by the instrumentation. If the sensor detected the 40- to 60-cps stall frequency, the $\dot{P}$ override would have opened the servo valve wider on each cycle of the stall frequency and, thereby, might have effected a recovery from stall.

The opening of the servo valve at about 8.6 seconds (fig. 12) indicates that the $\dot{P}_l$ set on the potentiometer (fig. 2) was not large enough to prevent the override from operating on the fuel flow cutback.

SUMMARY OF RESULTS

A manufacturer's standard fuel control was equipped with an overriding system which would take corrective action in the event of compressor stall or surge. It was desired to have the override reduce engine fuel flow quickly so as to recover the engine from stall or surge, and then increase fuel flow at a slower rate after recovery, to avoid repeated stalls and surges and permit successful completion of the acceleration. Either of two engine parameters was used to operate the override, tailpipe temperature or the derivative of compressor-discharge pressure. The investigation gave the following information:

Using tailpipe temperature, the override operated successfully. After control gains were properly set, surge and stall recoveries were effected, and the number of stalls and surges was reduced.

It was possible to accelerate the engine considerably faster on a richer accelerating schedule with the overriding system operating than with the standard fuel control, even though surge and stall were encountered.

If the override using tailpipe temperature failed to recover the engine from surge or stall, the engine temperature would still be held to some preset limit. Although the acceleration attempt would be unsuccessful, the engine temperature would be limited.

Dead time between temperature and fuel flow delayed the recovery from surge and stall from 0.15 to 0.30 second when temperature was used.

The derivative of compressor-discharge pressure was successful in effecting a recovery from surge but failed to recover the engine from stall. However, the sensor used to measure compressor-discharge pressure did not respond to the 40- to 60-cps stall frequency and thereby hindered the action of the override.

A fuel control equipped with an override using temperature as the control signal could be run with enriched schedules to yield much faster accelerations. If surge or stall were encountered during these rapid accelerations, the override would permit a safe, successful acceleration without the pilot's attention.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 15, 1956

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APPENDIX A

SYMBOLS

C	capacitor
K_n	gain of amplifier 2 when error is negative
K_p	gain of amplifier 2 when error is positive
$\dot{P}$	first derivative of compressor-discharge pressure with respect to time
R	resistor
s	Laplacian operator
T	tailpipe temperature, $^{\circ}F$

Subscripts:

m	measured value
l	limiting value
1,2,3 . . .	designation of resistor or capacitor from fig. 2

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APPENDIX B

EXPLANATION OF ELECTRONIC COMPUTER AND DERIVATIVE CIRCUITS

As is shown by figure 2, the circuit of amplifier 1 provides derivative action with a transfer function

$$-\frac{R_2C_1s}{1 + R_1C_1s}$$

This circuit provides essentially derivative action to the break frequency determined by R_1C_1. In operation R_1C_1 was set at 0.025 second, the break frequency then being about 6 cps.

In the electronic computer circuit (fig. 2) diode 1 acts as a switch and changes the gain across amplifier 2 when the signal at the output of amplifier 2 changes sign. This change in gain permits the servo valve to close slowly and open quickly. When the error is negative, signifying normal engine operation, the output of amplifier 2 is

$$K_n\text{Error} = -\frac{R_6R_5}{(R_6 + R_5)R_4}\text{Error}$$

where $R_3 = R_4$.

When the error becomes positive, indicating surge or stall has been encountered, its gain is increased to

$$K_p\text{Error} = -\frac{R_5}{R_4}\text{Error}$$

The servo valve is opening when the error is positive and closing or closed when the error is negative. The difference in opening and closing rates can be changed over a wide range if R_6 is made quite small.

Amplifier 3 (fig. 2) shapes the signal which opens and closes the servo valve. Diode 2 provides one of two transfer functions. When the error signal is negative and capacitor 2 is discharged, normal engine operation is taking place and diode 2 is conducting. Under these circumstances its transfer function is approximately $-\frac{R_8}{R_7}$ where $R_8 \ll R_9 + \frac{1}{C_2s}$.

When these conditions prevail, the output of amplifier 3 is negative and near zero ($R_8 << R_7$), and the servo valve is closed.

When the error signal becomes positive, indicating that stall or surge has been encountered, diode 2 no longer conducts, and the transfer function of amplifier 3 becomes

$$-\left(\frac{1}{R_7 C_2 s} + \frac{R_9}{R_7}\right)$$

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This is a proportional-plus-integral action where R_9/R_7 is the proportional gain and R_7C_2 determines the integrating rate. During the testing a very high integrating rate was maintained so that corrective action increased quickly while the engine remained in stall or surge. The time constant R_7C_2 was set at 0.0125 second, and the proportional gain at about 8 throughout most of the testing.

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3. Phillips, W. E., Jr.: Temperature-Control Study of Turbine Region of Turbojet Engine, Including Turbine-Blade Time Constants and Starting Characteristics. NACA RM E55L22, 1956.

4. Delio, G. J., and Stiglic, P. M.: Experimental Investigation of Control Signals and the Nature of Stall and Surge Behavior in a Turbojet Engine. NACA RM E54I15, 1954.

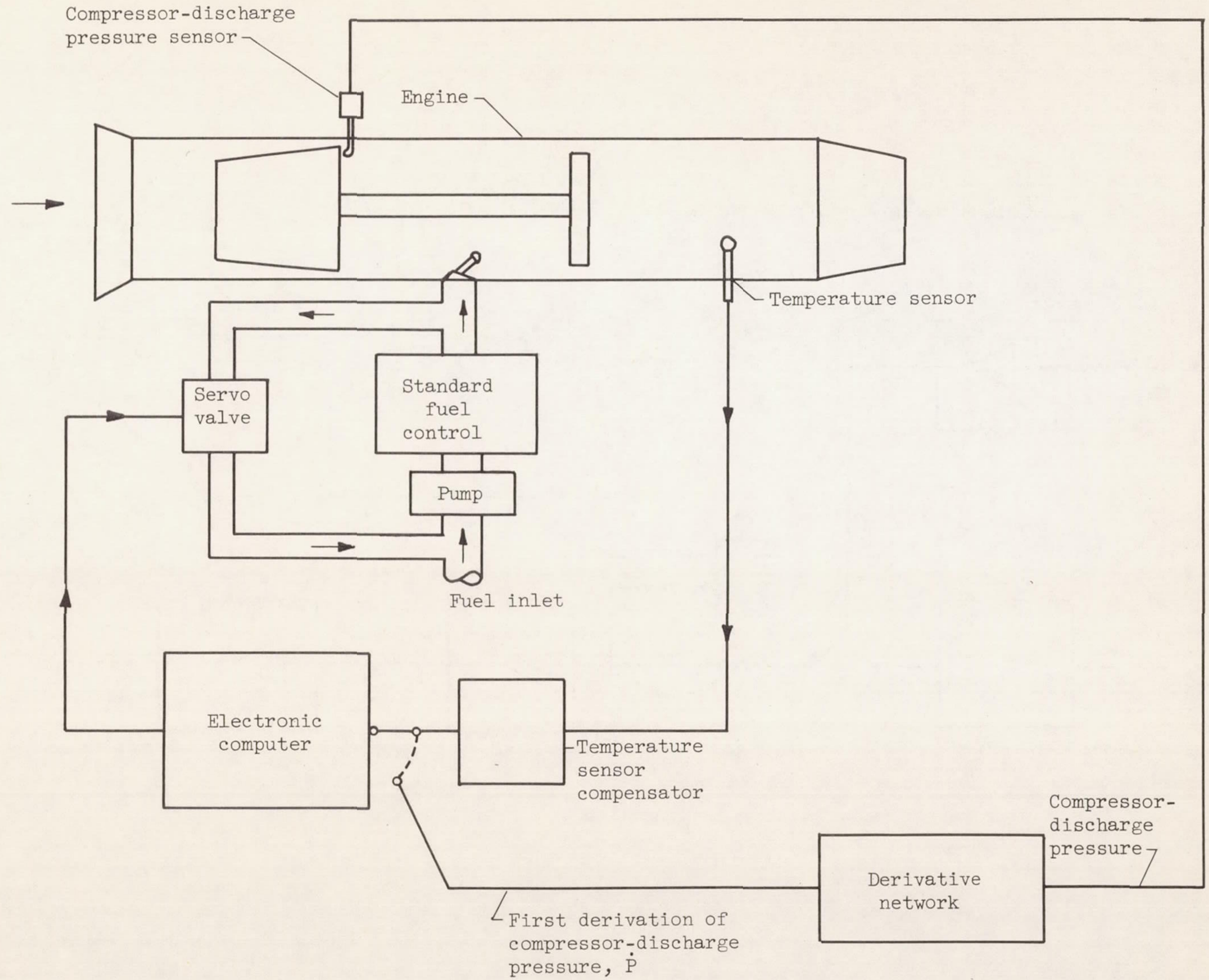

Figure 1. - Block diagram of test control system.

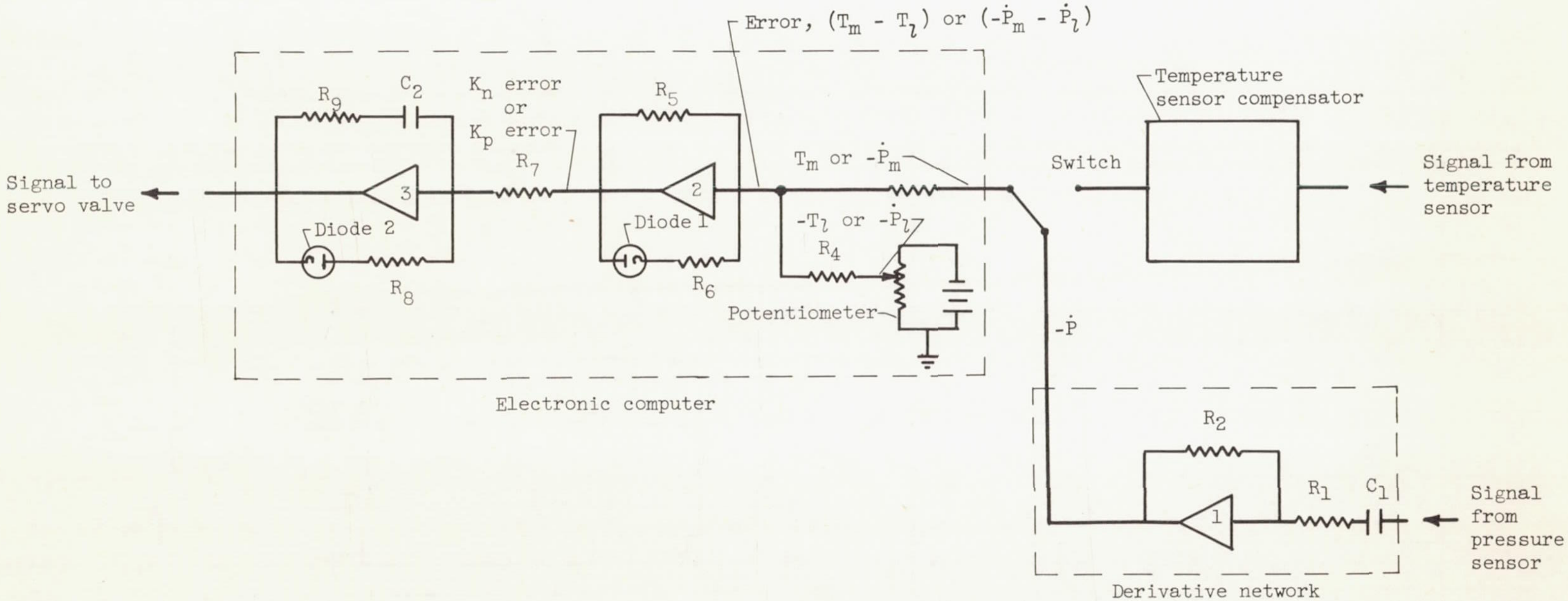

Figure 2. - Circuit diagram of derivative network and electronic computer.

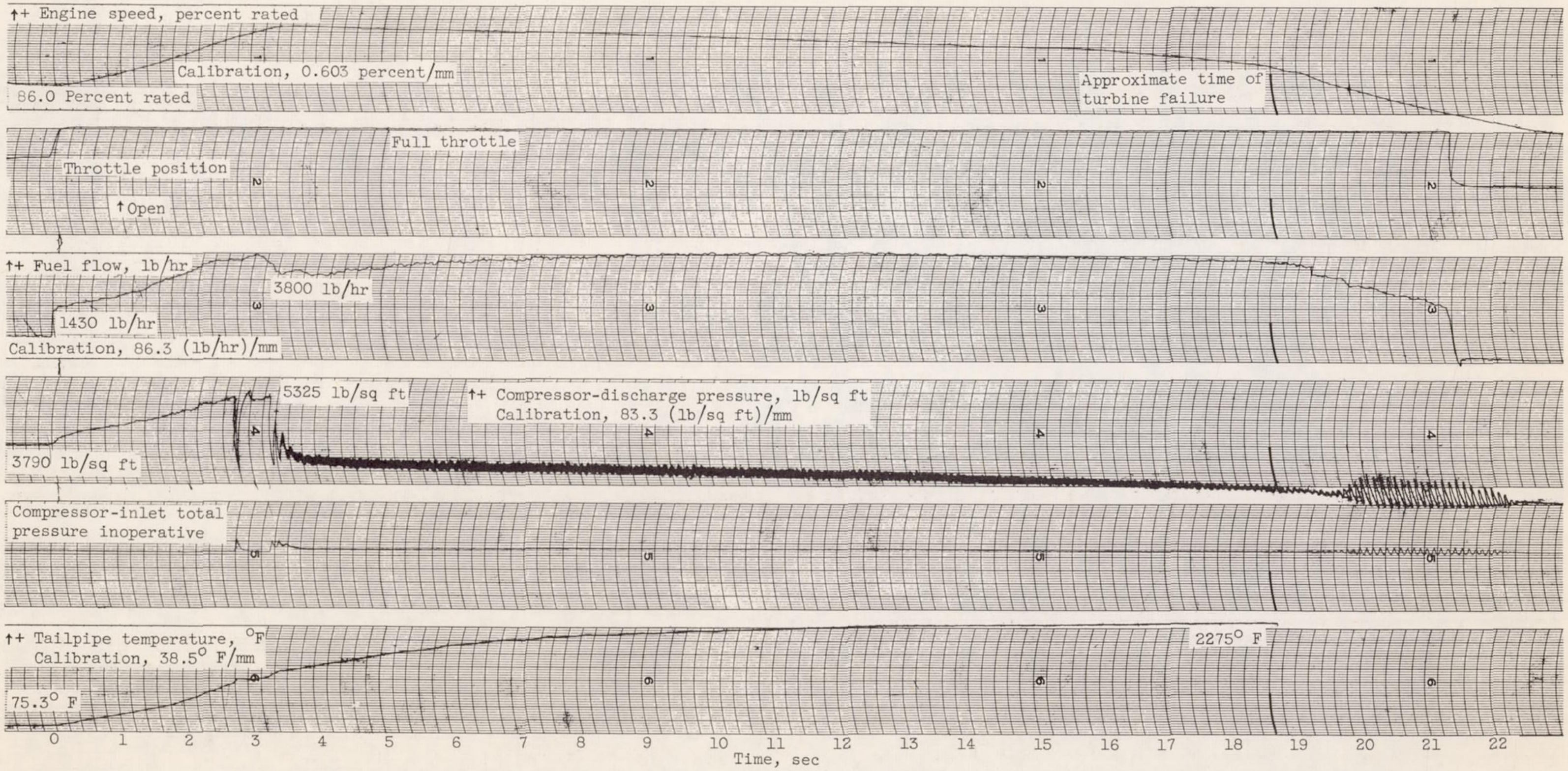

Figure 3. - Oscillogram of engine acceleration encountering surge and stall and resulting in turbine failure. Altitude, 35,000 feet; Mach number, 0.54; inlet-air temperature, -40° F.

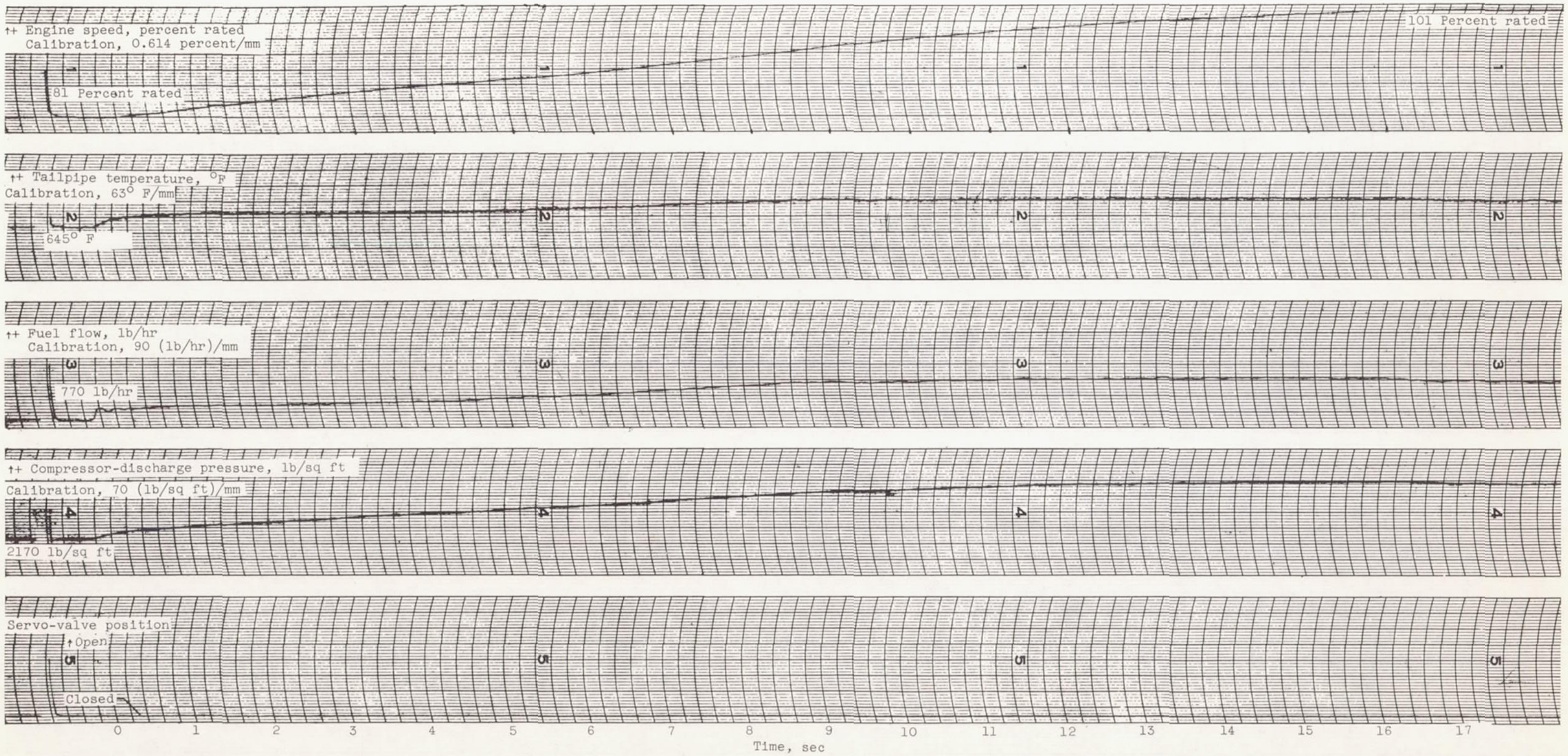

Figure 4. - Normal acceleration of test engine with standard fuel control. Altitude, 45,000 feet; flight Mach number, 0.68.

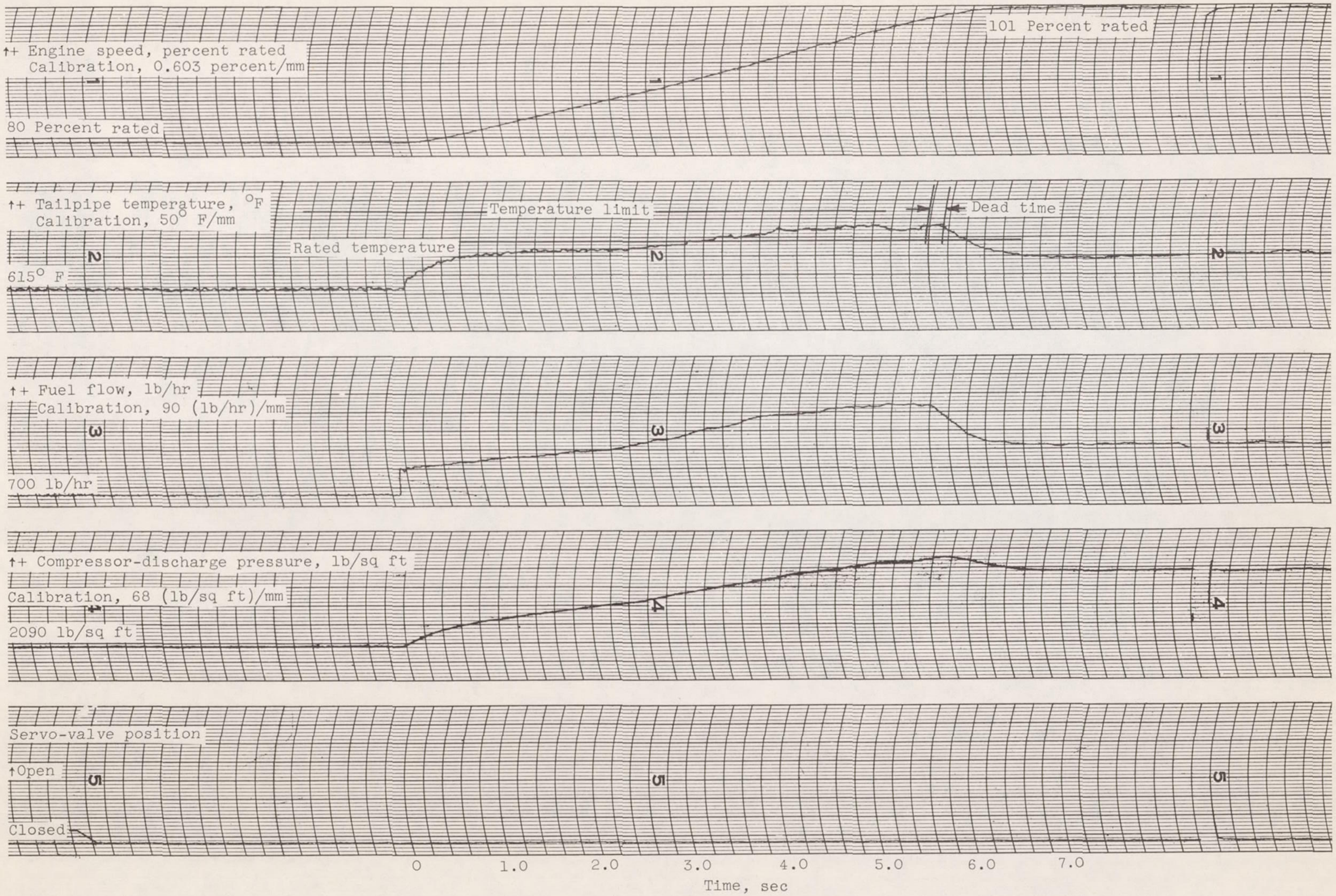

Figure 5. - Transient run with enriched acceleration schedule. Altitude, 45,000 feet; flight Mach number, 0.68.

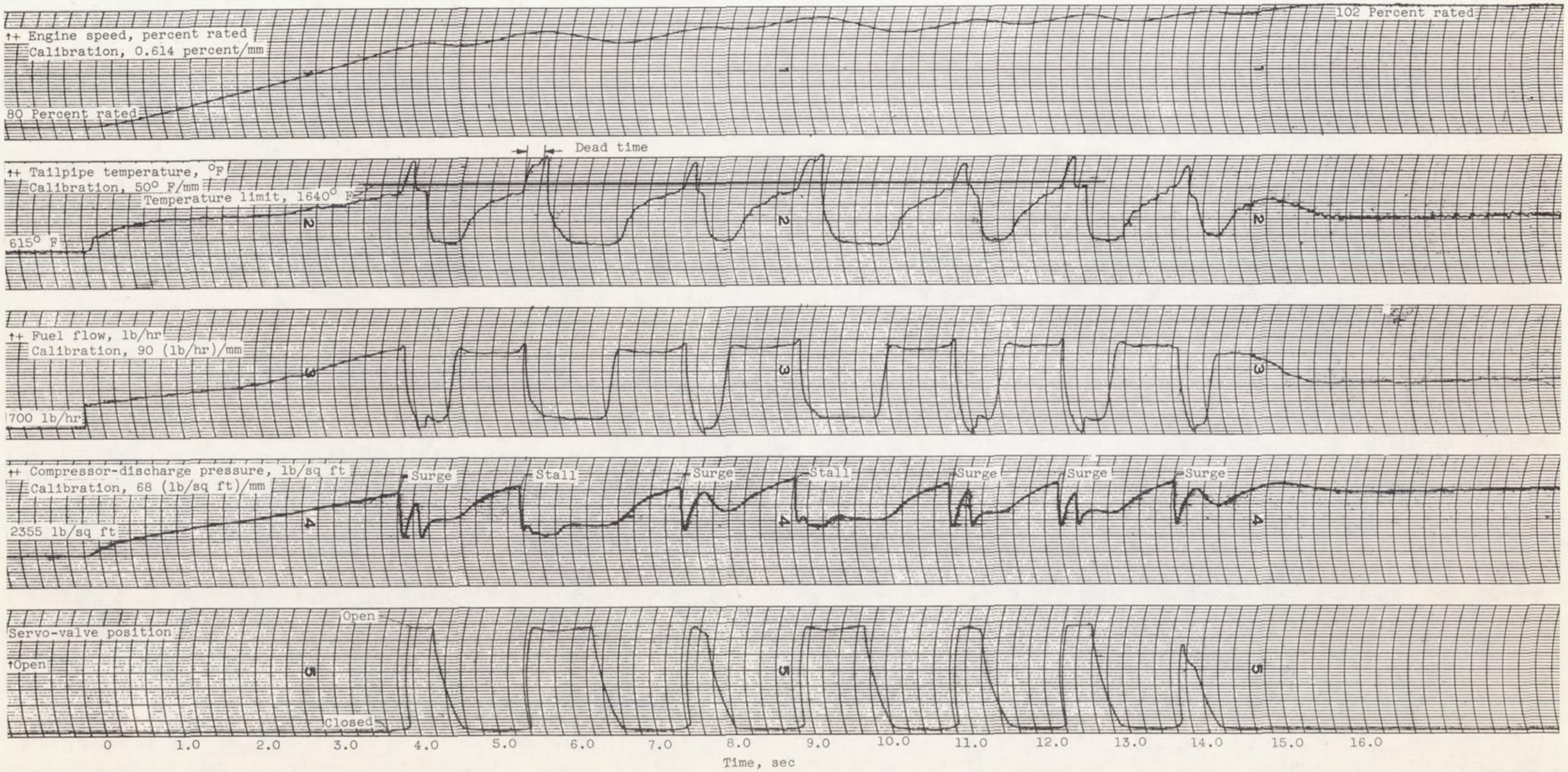

Figure 6. - Successful acceleration showing override recovering engine from surge five times and from stall twice. Altitude, 45,000 feet, flight Mach number, 0.68.

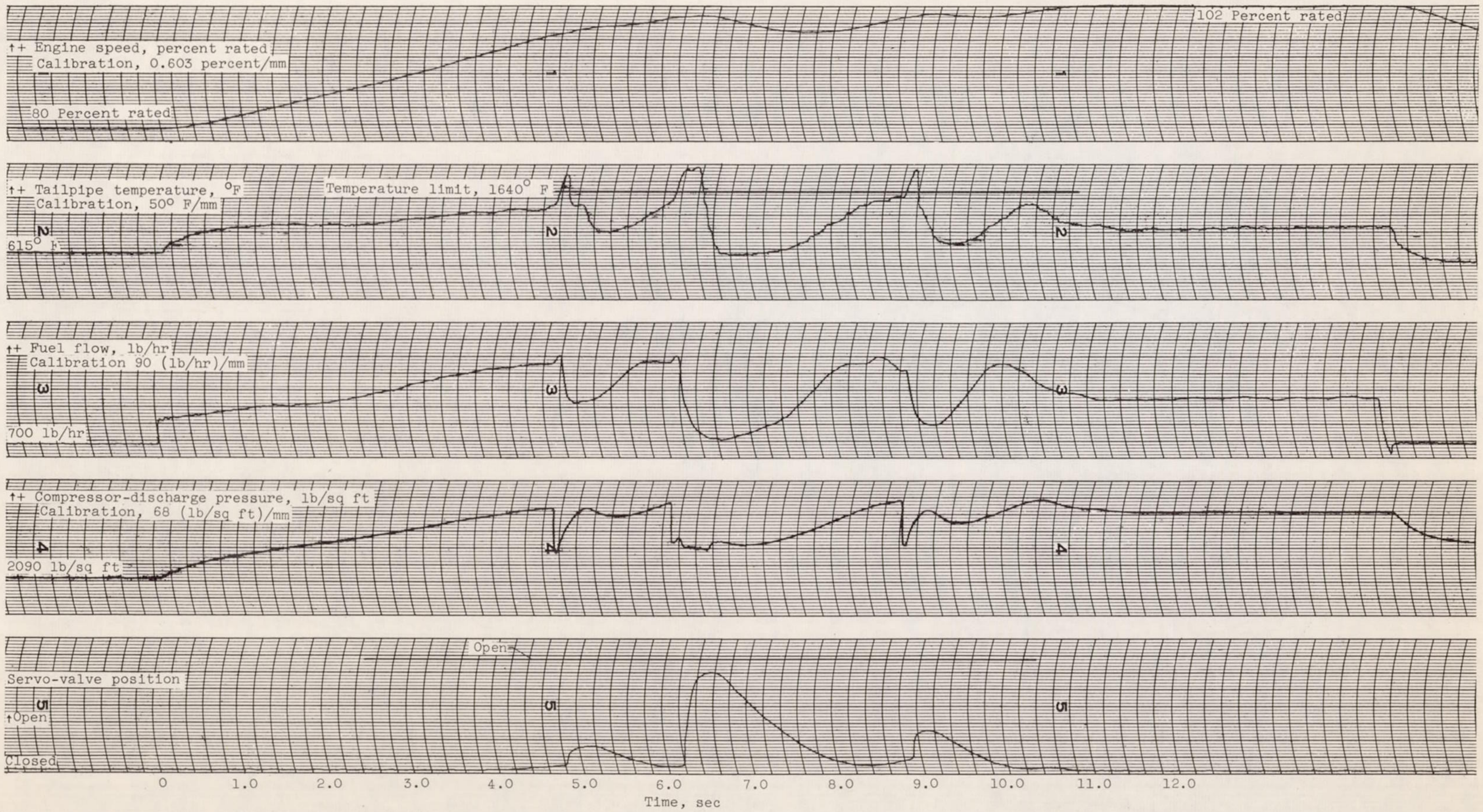

Figure 7. - Successful acceleration showing stall and surge recovery with override set at slower rate than for transient of figure 6. Altitude, 45,000 feet; flight Mach number, 0.68.

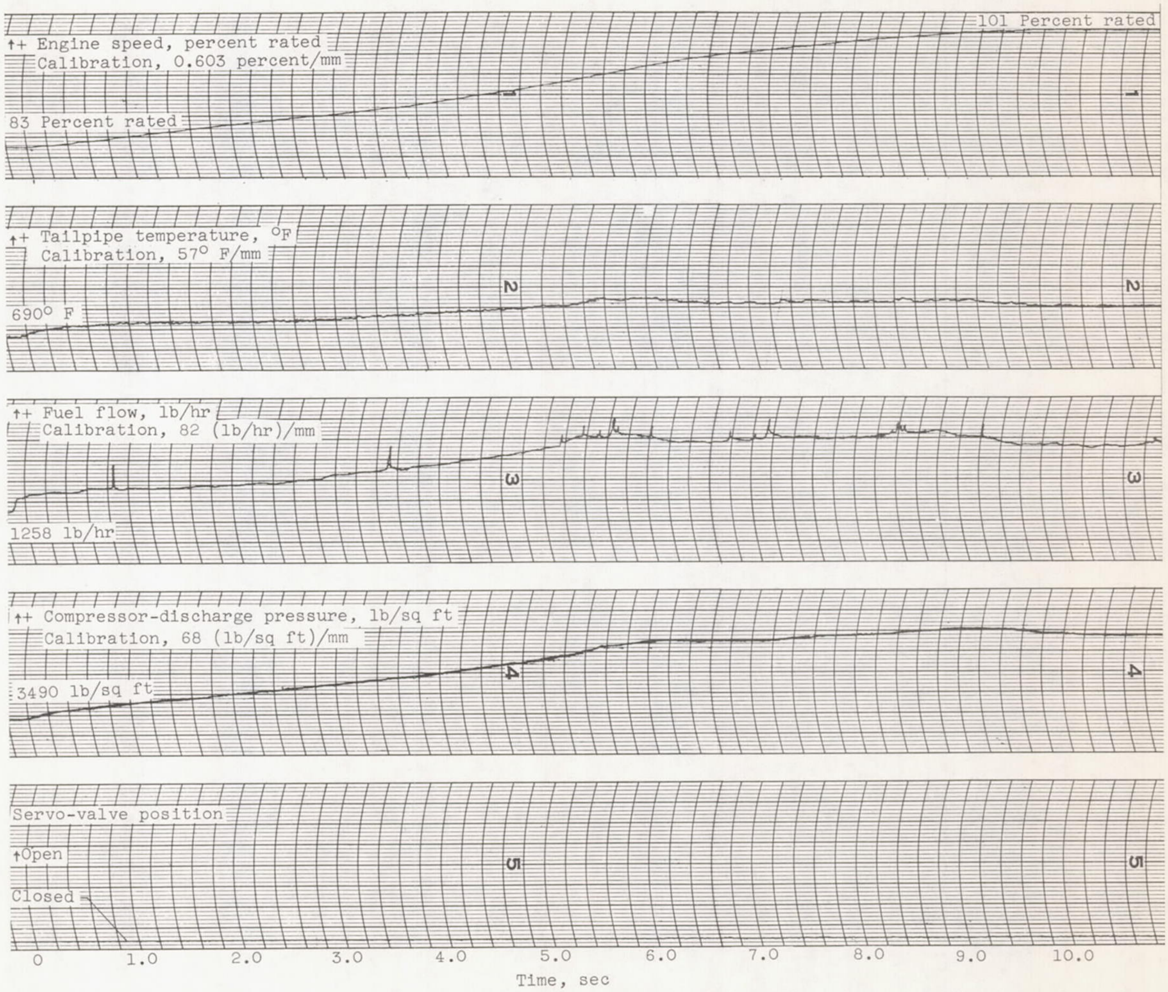

Figure 8. - Normal acceleration of test engine with standard fuel control. Altitude, 35,000 feet; flight Mach number, 0.54.

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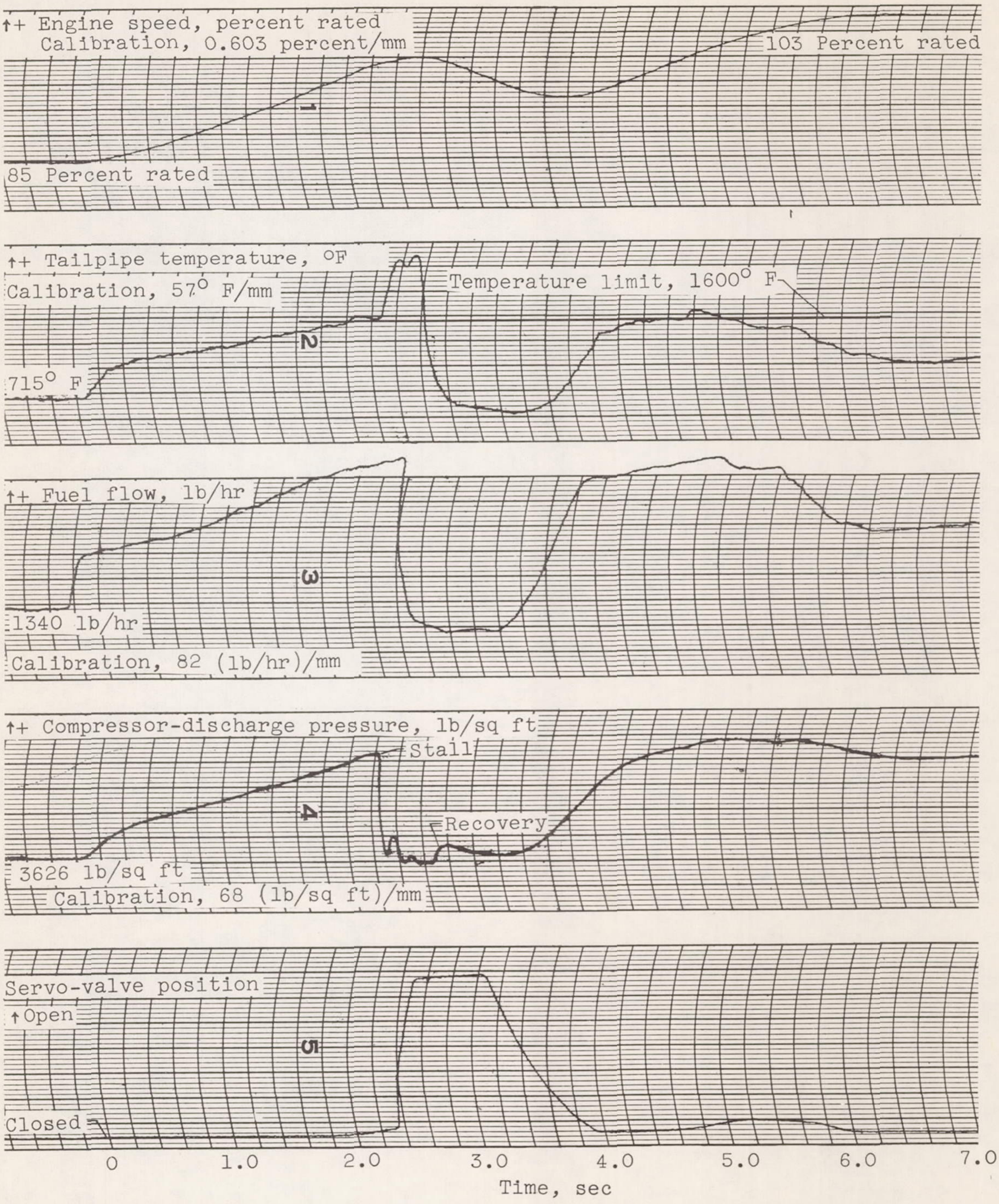

Figure 9. - Successful acceleration showing override recovering engine from stall. Altitude, 35,000 feet; flight Mach number, 0.54.

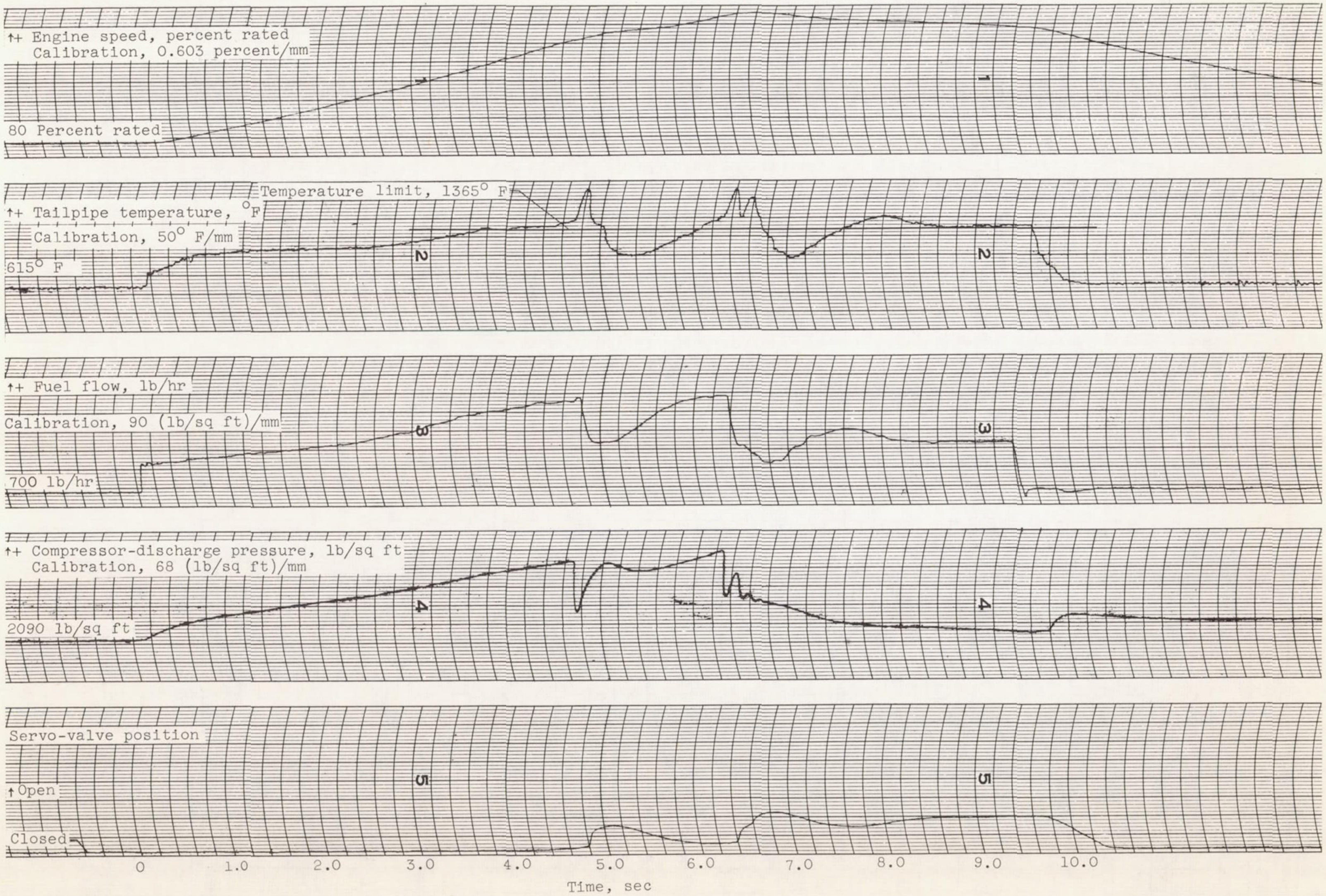

Figure 10. - Unsuccessful acceleration attempt encountering stall. Override control limits temperature to preset limit. Altitude, 45,000 feet; flight Mach number, 0.68.

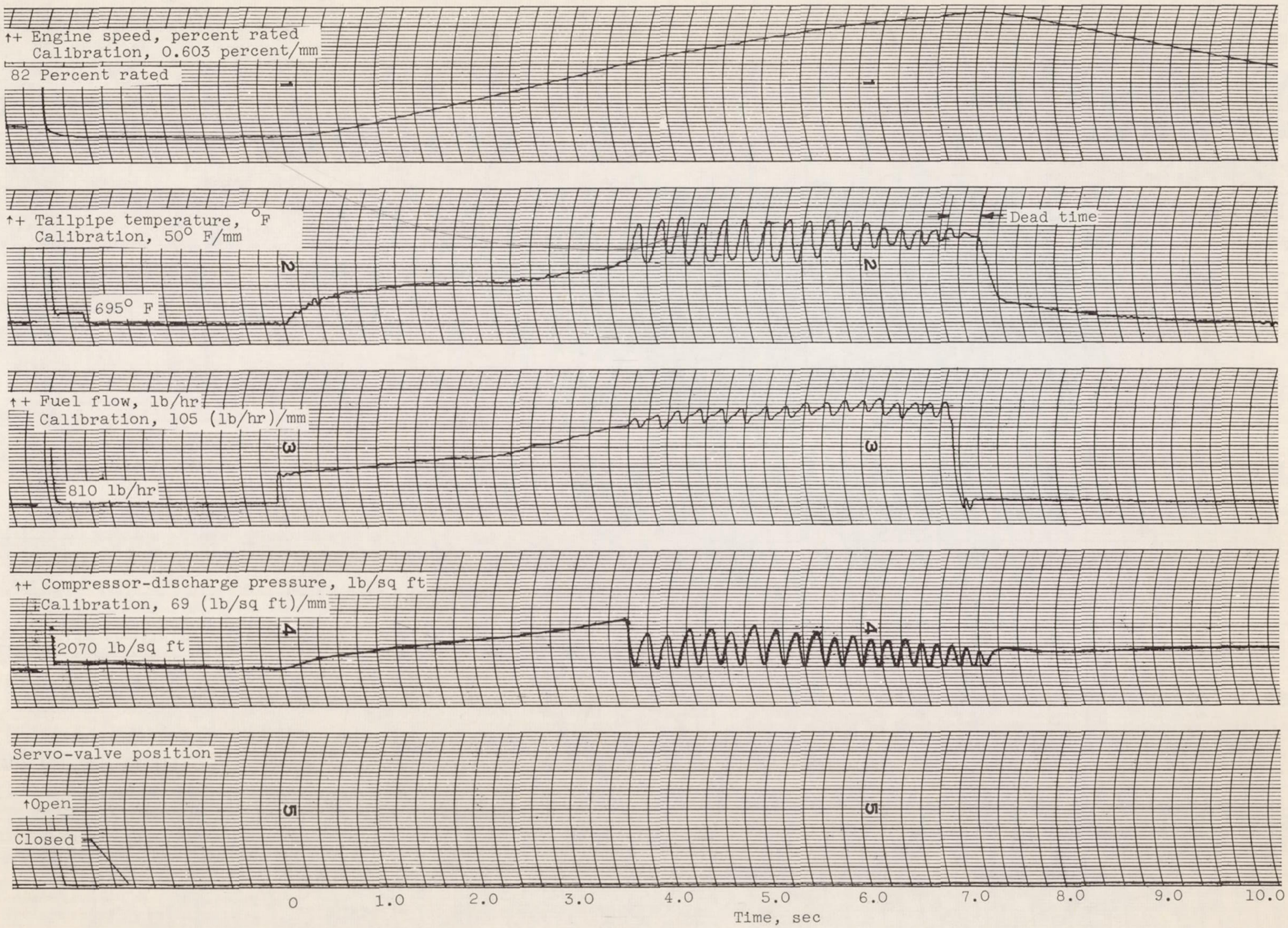

Figure 11. - Transient encountering surge showing temperature-to-fuel-flow dead time. Override inoperative. Altitude, 50,000 feet; flight Mach number, 0.8.

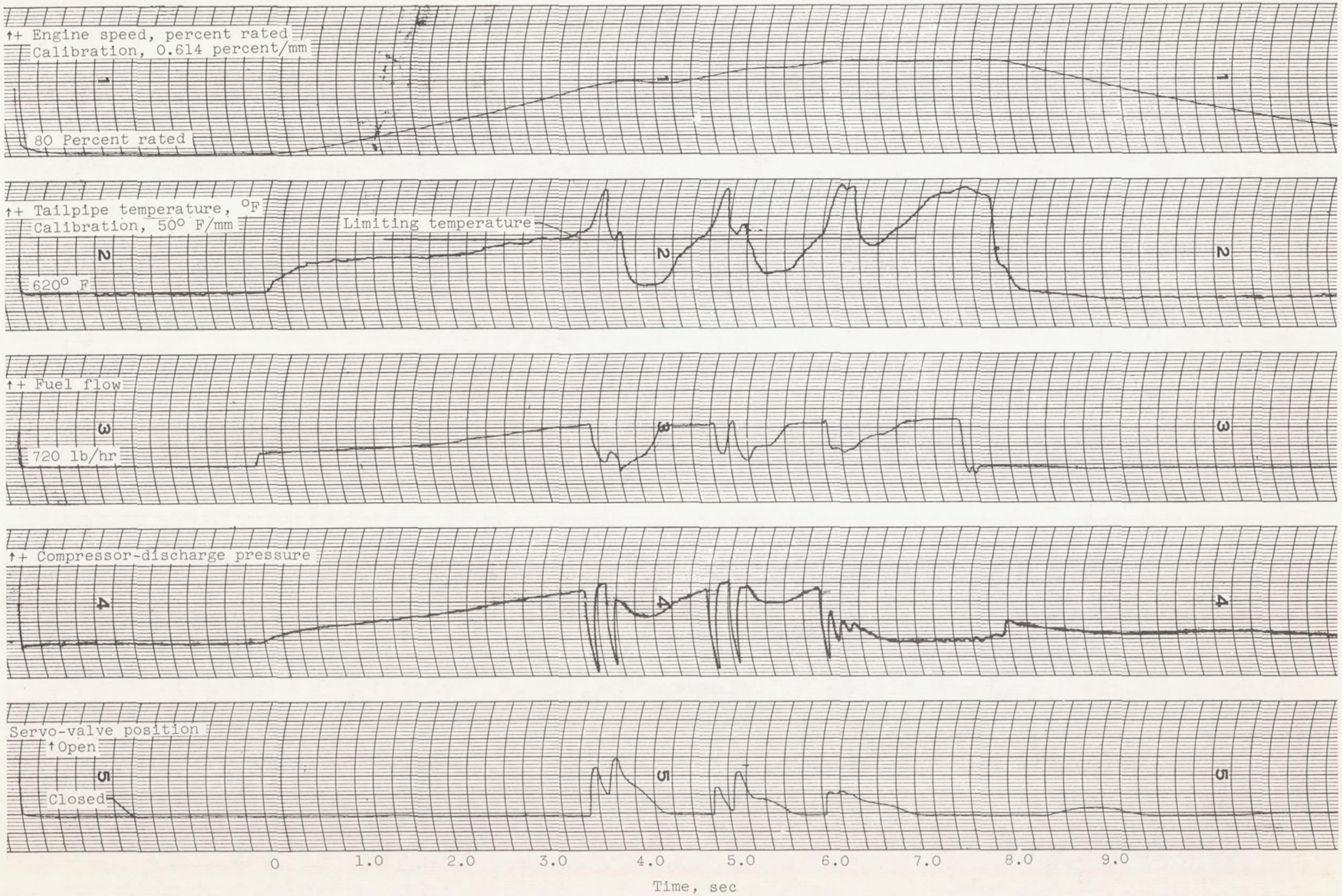

Figure 12. - Record of override operating with compressor-discharge pressure derivative as control signal showing successful surge recovery and unsuccessful stall recovery. Altitude, 45,000 feet; flight Mach number, 0.68.