Oct. 11, 1960 B. S. HEGG ET AL 2,955,416

COORDINATED FUEL FEED AND EXHAUST JET AREA CONTROL FOR GAS TURBINE ENGINES

Original Filed May 15, 1952

4 Sheets-Sheet 1

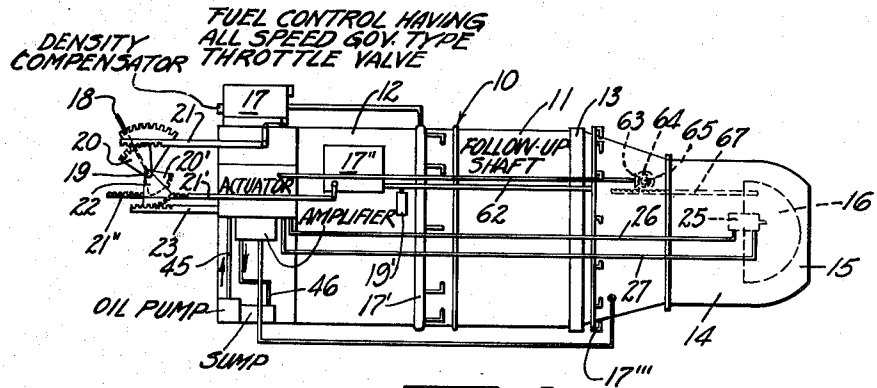


FIG 1

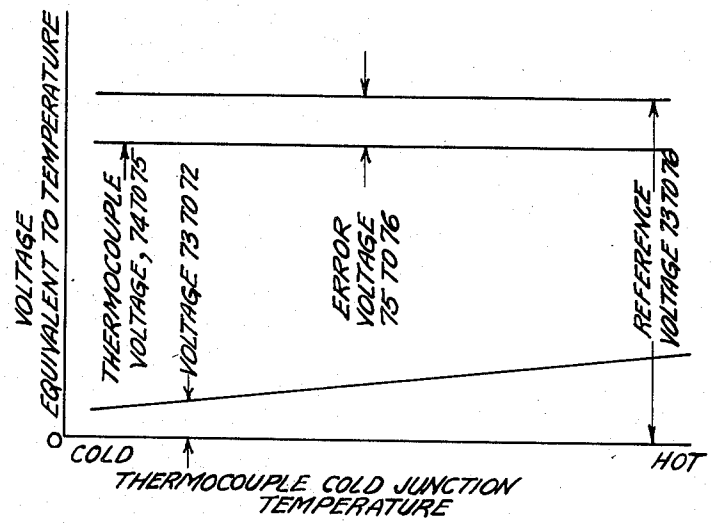


FIG. 5

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4 Sheets-Sheet 2

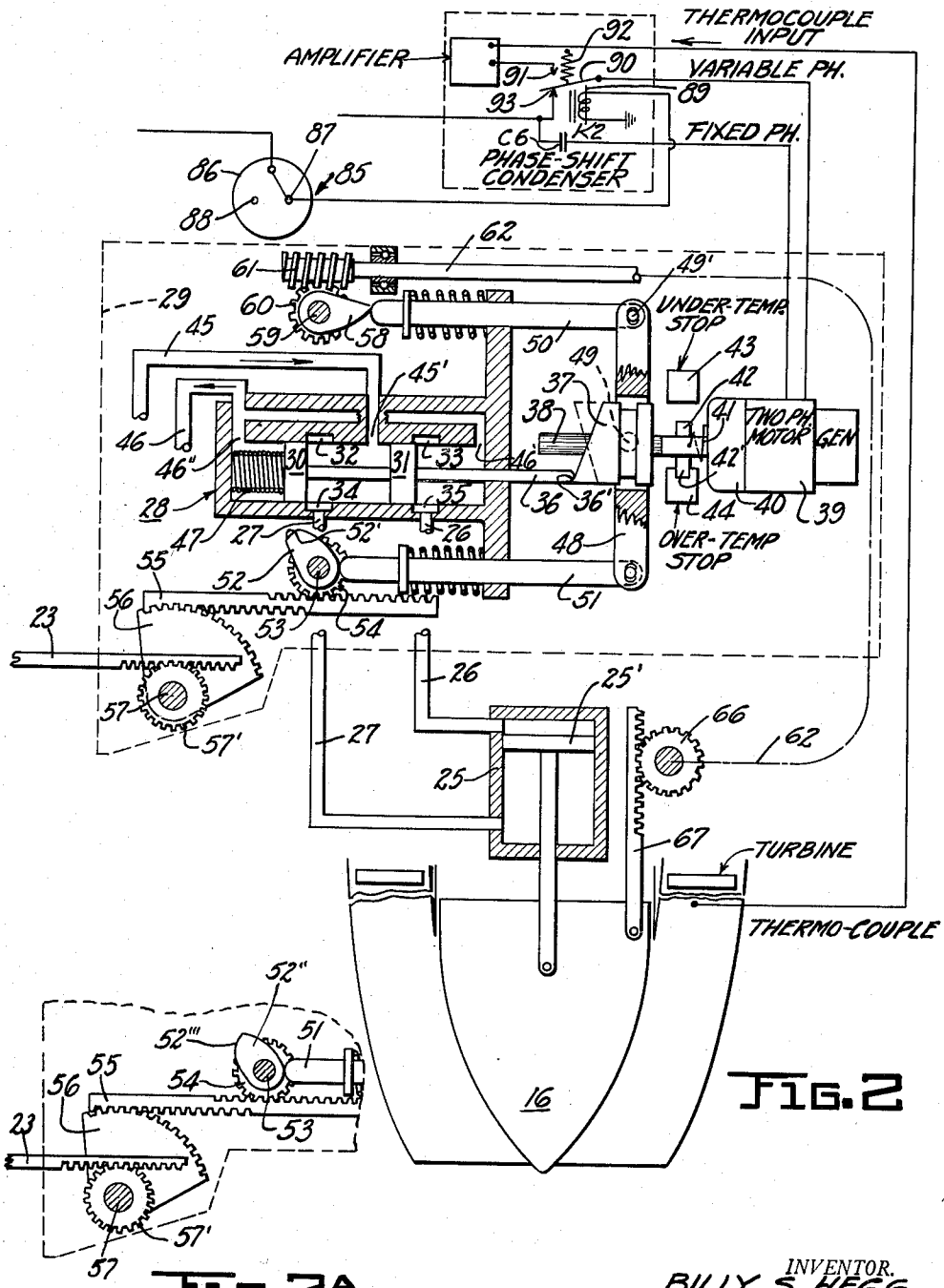


FIG. 2

FIG. 2A

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4 Sheets-Sheet 3

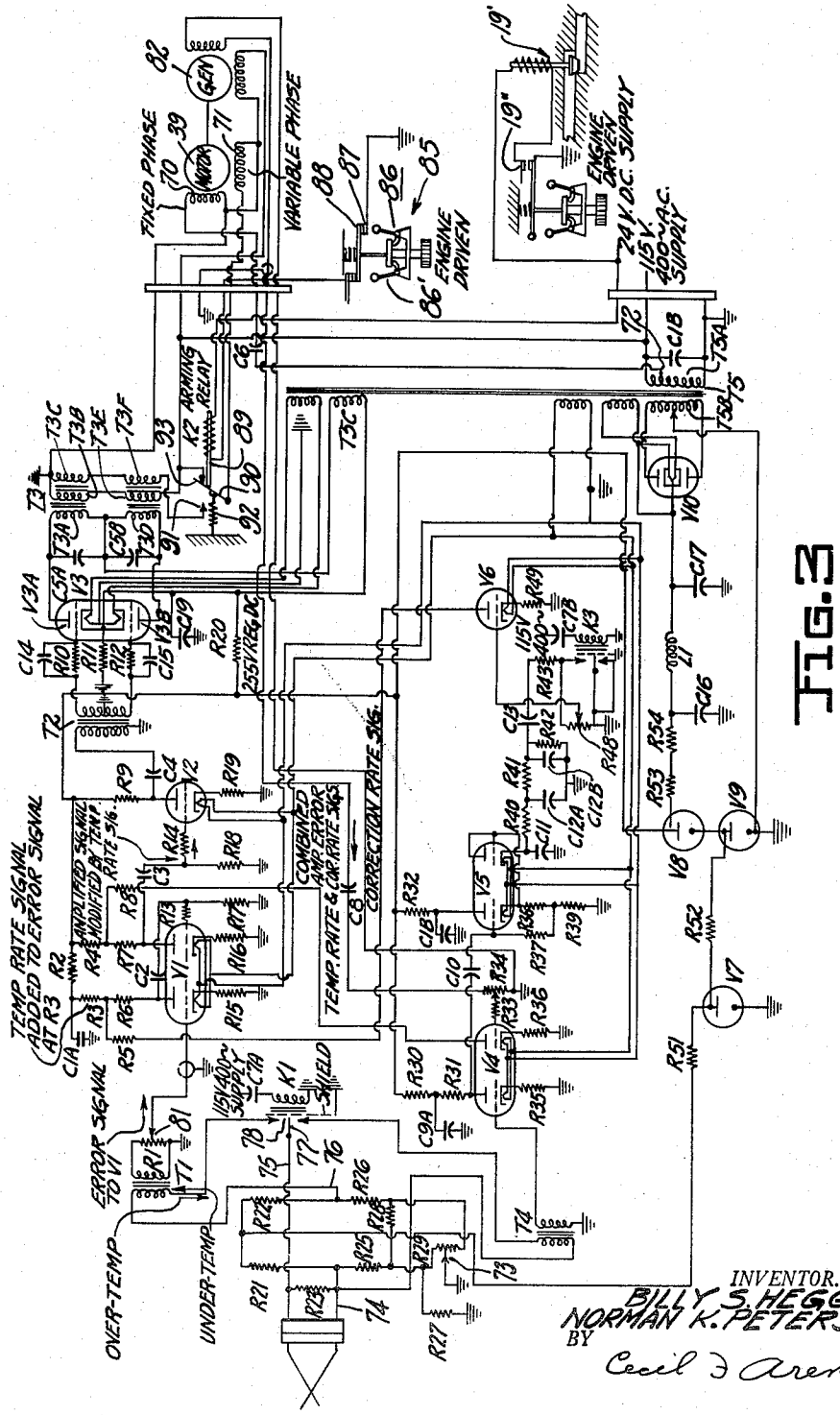


FIG. 3

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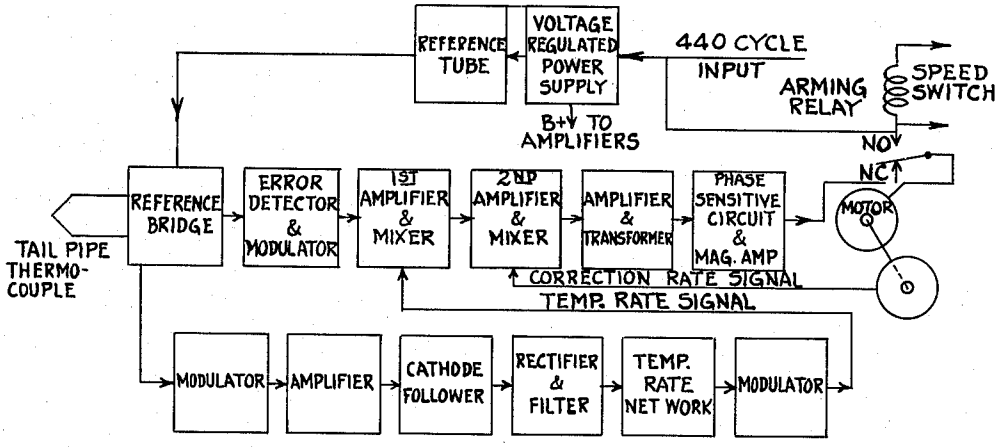


FIG. 4

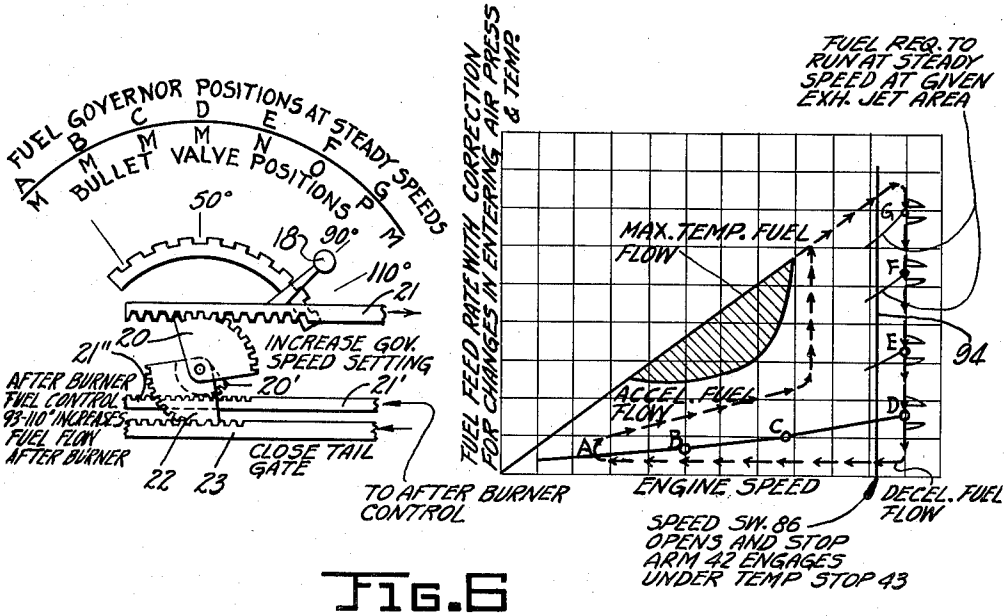


FIG. 6

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2,955,416

COORDINATED FUEL FEED AND EXHAUST JET AREA CONTROL FOR GAS TURBINE ENGINES

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Continuation of application Ser. No. 287,926, May 15, 1952. This application Oct. 6, 1958, Ser. No. 765,675

4 Claims. (Cl. 60—35.6)

This application is a continuation of our application Serial No. 287,926, filed May 15, 1952, now abandoned, which is a continuation-in-part of our application Serial No. 212,566, filed February 24, 1951, now abandoned. Both applications relate to controls for gas turbine engines, and particularly to controls of a type wherein the rate of fuel feed and the area of the exhaust jet or nozzle are coordinated over a predetermined portion of the power throttle range subject to the action of an override device responsive to temperature, speed or other operating condition or parameter. An example of such a control is illustrated in the copending application of Frank C. Mock, Serial No. 156,980, filed April 20, 1950, now abandoned (common assignee).

An object of the instant invention is to provide a control mechanism of the type specified which may be readily adapted to certain desired conditions of engine operation. Thus, in the example illustrated, the improved control will automatically maintain the exhaust jet or nozzle at maximum area at power lever positions and engine speeds below a predetermined value; and at power lever positions and engine speeds above such value and at tailpipe temperatures below a predetermined value, the exhaust jet area will vary in response to adjustment of said lever; and should the tailpipe temperature rise beyond the set or predetermined temperature with the exhaust jet or nozzle at any area less than maximum, the power lever control will be overridden and the exhaust jet area will be automatically increased until the tailpipe temperature drops to a safe value. Should the pilot attempt to reduce the area of the exhaust jet to a value which will produce unsafe tailpipe temperatures, the power lever control will again be overridden and jet nozzle area will vary as a function of a tailpipe temperature only.

Another object is to coordinate the action of a hydraulic and an electronic control for regulating the exhaust jet area of a turbojet engine.

A further object is to improve the control mechanism disclosed in the application of Frank C. Mock above noted.

Another object is to coordinate the action of a hydraulic mechanism with an engine temperature sensing electronic control for regulating the exhaust area of a gas turbine engine.

A still further object resides in the provision of mechanism operatively connected to an engine throttle and to an exhaust area control device for selecting an effective exhaust area corresponding to a given throttle position regardless of whether the throttle setting is in the power range or afterburner range.

A yet further object is to provide an exhaust area control mechanism for a gas turbine engine operatively connected to an engine throttle, which coordinates fuel feed with exhaust opening, and to an engine temperature sensing apparatus which automatically modifies the exhaust opening.

Another important object is to provide a mechanism

responsive to throttle movement through the afterburner range for establishing a predetermined exhaust area opening and responsive to electronic engine temperature sensing means for modifying the exhaust area opening.

It is one of the aims of this invention to coordinate control of the engine exhaust area, the main fuel control and afterburner control with throttle position subject, however, to modification when engine temperature is beyond a predetermined value.

The foregoing and other objects and advantages will become apparent in view of the following description taken in conjunction with the drawings, wherein:

Figure 1 is a view, principally in elevation, of a turbojet engine having operatively associated therewith a control embodying the features of the instant invention;

Figure 2 is a sectional schematic view of the hydraulic actuator for the jet nozzle area varying valve or bullet;

Figure 2*a* illustrates a modified cam construction;

Figure 3 is a wiring diagram of the electronic temperature responsive control and amplifier control for the hydraulic actuator;

Figure 4 is a block diagram of the circuitry of Figure 3;

Figure 5 is a graph illustrating the operation of the bridge circuit of Figure 3; and

Figure 6 is a curve chart illustrating the operation of the control.

Referring to Figure 1, a turbojet engine is shown more or less diagrammatically at **10**; it includes a burner section **11**, and air adapter or header section **12** detachably connected to the front end of the burner section and adapted to direct air under pressure from an axial flow compressor not shown to the burners, where the air mixes with the fuel discharged from the burner nozzles to promote combustion, the expanded air and products of combustion being discharged through a turbine section **13**, tailpipe **14**, and a reaction jet or exhaust nozzle **15**. The arc of the exhaust jet is variable by suitable means such as a bullet valve or cone **16**, mounted to move inwardly and outwardly of the exhaust jet on suitable guides, not shown.

Fuel is supplied to a main fuel manifold **17'** of the main burner system by a suitable fuel control device generally indicated at **17**, which is preferably of the type disclosed in the copending application of Frank C. Mock aforementioned, and wherein the engine speed as selected by the pilot is automatically maintained by an engine driven all-speed governor at all altitudes irrespective of changes in the pressure and/or temperature of the air flowing to the engine. A pilot actuated power control lever is indicated at **18**; it is secured on a shaft **19** and the latter is operatively connected to the governor valve of the fuel control unit **17** through a gear **20** and rack **21**. Also secured on shaft **19** is a gear **22** in mesh with a rack **23**, which projects into the hydraulic actuator for a purpose to be described.

The engine of Figure 1 is further equipped with an afterburner fuel system of the type shown in the copending application of Frank C. Mock, et al., Serial No. 89,054, filed April 22, 1949, now Patent No. 2,774,215, assigned to a common assignee, and comprises an afterburner fuel control device **17''** and an afterburner manifold **17'''**. The pilot actuated power control lever or throttle **18** is also connected to the afterburner control device **17''** through a mutilated gear sector **20'** and linkage **21'**, the latter including a rack portion **21''**, which is arranged to be engaged by the mutilated gear sector **20'** only after the throttle has been moved through 90°, as best shown in dotted lines, Figure 6. That is, it is not until after the lever **18** has been moved through the power range, 52° to 90°, that the afterburner system becomes effective as an additional fuel supply, thus supple-

menting the main fuel supply to the engine. The addition of fuel at the proper time beyond that supplied by the main fuel control augments the engine thrust. Therefore, the range between 93° and 110° of the pilot control member is known as the thrust augmentation range. The 3° allowed between 90° and 93° permits some throttle movement at the end of the power range, before going into the afterburner range. Movement of the throttle between 90° and 93° has no further effect on the power range.

The bullet valve or cone **16** is repositioned or reset by means of a hydraulic servo motor generally indicated at **25** and having mounted therein a servo piston **25'**, note Figure 2. High pressure oil or hydraulic fluid is conducted to the cylinder **25** on opposite sides of piston **25'** by way of high pressure oil lines **26** and **27**, which lead from a servo valve **28** located in the housing **29** of the actuator mechanism. The servo valve **28** (Figure 2) comprises a suitable cylinder having slidably mounted therein a pair of valve pistons **30** and **31**, which control the exhaust areas to the annular lands or recesses **32** and **33**, from which ports **34** and **35** lead to the oil lines **27** and **26**. The valve pistons **30** and **31** are carried by a slide rod **36**, which constitutes a cam follower and has a cam surface **36'** at its free end engaging the active surface of a motor driven cam **37**, splined for limited longitudinal sliding movement on a shaft **38**, adapted to be driven by a motor **39** through a gear reduction unit **40**, the said motor being a two-phase servo motor controlled in a manner to be described. When the power is off, a spring **41** returns or rotates the motor or armature shaft **38** back to a position where the one end **42'** of a stop arm **42** carried by the shaft engages an under-temperature stop **43**. In actual practice, the spring **41** is located on the gear reduction unit **40** and the latter drives cam **37** through an additional reduction unit, but for purpose of illustration, the said spring is shown exteriorly of the reduction unit and surrounding the shaft **38**. An overtemperature stop **44** is also adapted to be engaged by the end **42'** of arm **42** under certain conditions of operation to be described.

Hydraulic fluid such as oil under pressure is conducted to the servo valve **28** through oil line or conduit **45** and port **45'**, and is exhausted or drained therefrom by way of exhaust ports **46'** and **46''** and oil line or conduit **46**. A spring **47** normally urges the cam end **36'** of the piston or follower rod **36** against the active surface of the cam **37**.

The cam **37** is actuated axially on the splined portion of the shaft **38** by means of a link bar **48**, which is pivotally connected at **49** to said cam, the bar **48** having a pivot and slot connection **49'** at one end to a slidable rod or cam follower **50** and at its opposite end being pivoted to a similar rod or follower **51**.

A throttle cam **52** is secured on a shaft **53**, which is rotated by means of a pinion **54**, adapted to engage a rack bar **55**, the latter having teeth in mesh with those of a segmental gear **56**, secured on a shaft **57**. Also secured on the latter shaft is a pinion **57'** having teeth in mesh with those of the rack bar **23** and which is actuated in response to adjustment of the pilot's control lever **18**, Figure 1. The cam **52**, when rotated, actuates the follower rod **51**.

The follower rod **50** is actuated by means of a follow-up cam **58**, which is secured on a shaft **59**. Also secured on the same shaft is a pinion **60**, the teeth of which are in mesh with those of a worm **61**, secured on the one end of a follow-up shaft **62**, the latter extending back to the tailpipe section and at its opposite end being provided with a bevel gear **63**, note Figure 1, in mesh with a similar gear **64**, secured on the adjacent end of a shaft **65**. Shaft **65** projects through and has bearing in the wall of the tailpipe and at its inner end has secured thereon a pinion **66**, the teeth of which are

in mesh with those of a rack gear **67**, connected to the bullet valve **16**, note Figure 2.

Preferably, the contour of cam **52** is such that it is ineffective to move the servo valve follower rod **51** through the idle range of adjustment, 0° to 52°, of the pilot's control lever **18**. Beyond that range, or throughout the power range, 52° to 90°, the cam **52** acts to reset cam **37** longitudinally on the shaft **38**. Rotation of the lever **18** from 93° to 110° is ineffective to move the follower rod **51** since the face **52'** of the cam **52** on which the follower **51** rides is of constant radius in this range. Figure 2*a* illustrates a modified cam construction wherein cam **52''** functions in the same manner as cam **52** between 0° to 90° throttle movement, but effects a change in exhaust area opening from 93° to 110° throttle rotation. The cam **52''** is contoured so that when the throttle is moved into the afterburner range, that is, beyond 93° rotation, the follower rod **51** moves to the left, Figure 2, along the decreasing radius **52'''** of the cam **52''**, thus moving the follower **36** to the left to thereby connect the servo motor **25** to the hydraulic source for moving the cone **16** upwardly to increase the exhaust area opening. Afterburner control and exhaust area opening are coordinated with throttle position in the 93° to 110° range, as best shown in Figure 2*a*.

It will be noted that the effective position of the follower rod **36** is also governed by the angular position of cam **37**, which is a function of engine or turbine temperature and is capable of overriding the power lever or throttle control.

To preclude the introduction of afterburner fuel into the engine before it is capable of handling fuel in excess of the main supply, a solenoid valve **19'** is interposed in the afterburner system between the afterburner control device **17''** and the afterburner manifold **17'''**. Energization of the solenoid valve is controlled by an engine governor operated switch **19''**. After a predetermined engine speed has been attained, which speed may approach maximum engine speed, the solenoid valve **19'** is opened, thus connecting the manifold **17'''** to the afterburner control device.

The follow-up cam **58** which is connected to the cone-shaped valve **16** through interconnecting linkage, as shown, is contoured so that rotation of the cam due to movement of the cone will result in a substantially linear relationship between thrust vs. throttle angle.

The motor **39** is controlled electronically as a function of engine temperature subject to modification as a function of engine speed by the circuit shown in Figures 3 and 4 and which will now be described. In the wiring diagram of Figure 3, capacitors are commonly indicated by C; resistors by R; transformers by T; tubes by V; chokes by L; and choppers and relays by K.

At the right hand side of Figure 3 the motor **39** is shown diagrammatically as having a pair of field windings **70** and **71**, one (**70**) of which constitutes a fixed phase and the other (**71**) a variable phase winding. The winding **70** is connected in series with a capacitor C6 to a tap **72** on the primary of power transformer T5, which capacitor introduces a 90° phase shift between the fixed and variable phase windings required for maximum torque of motor **39**. The primary T5A of T5 is supplied with a 400 cycle A.C. input from a suitable source, not shown. The high voltage mid-tapped secondary T5B of T5 is connected to the rectifier tube V10 in a full-wave rectifier circuit which changes the 400 cycle per second sine wave into a pulsating direct current with 800 positive peaks per second, which is smoothed by the low-pass filter circuit including C16, L1, C17, R53, R54 and voltage regulator tubes V8 and V9. The direct current supply, as regulated by tubes V8 and V9, aids in eliminating amplifier gain variations and the effect thereof on control stability. The regulated voltage across V9 provides the required voltage for reference tube V7 and the dropping resistor R52. Tube V7 is preferably of

the cold cathode glow discharge type designed for good voltage stability with a negligible temperature coefficient.

The reference bridge circuit includes a network of precision wire wound resistors R21, R22, R25, R26, R28, and R29, which provide an accurate adjustable reference voltage for comparison with the voltage generated by the thermocouple and also provide for cold junction compensation. Cold junction compensation is provided because the motor control amplifier is required to operate as a function of the hot junction temperature only and not from the thermocouple voltage, which is determined by the difference between the hot and cold junction temperatures, the latter temperature varying with change in its ambient temperature. We therefore make a correction for variation in ambient temperatures by utilizing a resistor R25, which is designed so that its resistance varies with changes in temperature and the voltage from 73 to 74 becomes a function of the thermocouple cold junction temperature. As the cold junction temperature increases, the voltage output of the thermocouple will decrease for a constant hot junction temperature, but the voltage across the temperature compensating resistor R25 will increase sufficiently to make the voltage from 73 to 75 independent of the cold junction temperature. This circuit operation is shown graphically in Figure 5. The magnitude of the error voltage developed between 75 and 76 is proportional to the temperature difference between the amplifier calibration (adjustment of R29) and the thermocouple hot junction temperature. The error voltage polarity is determined by the relative magnitudes of the two temperatures, viz. 75, is positive with respect to 76 for thermocouple temperatures greater than the calibration or set temperature and negative for temperatures lower than the calibration temperature. The resistors R23 and R27 have been added for "safe failure." Thus, should the thermocouple circuit open external to the amplifier or motor control circuit, R23 completes the bridge circuit and maintains the equivalent of an under-temperature condition across the bridge. Under normal conditions, R23 has negligible effect on the bridge circuit. The resistor R27 simulates under-temperature operation should the wiper arm of potentiometer R29 open. In case of either failure, the motor control circuit will still "arm" the actuator control above the speed setting of the speed switch 86 but will not provide a safety override for the throttle control.

The error detector and modulator circuits include transformer T1, mechanical modulator or chopper K1, and capacitor C7A. A square wave voltage is developed across the secondary of the transformer T, and is proportional to the error signal from the reference bridge. This voltage is in phase or 180° out of phase with the 400 cycle supply, depending upon the error voltage polarity. The error voltage, i.e. the difference between the thermocouple and reference voltages, is modulated by the mechanical chopper K1 at the supply voltage frequency to permit the use of A.C. amplifiers. At tailpipe temperatures above or below the calibration temperature, current will flow in the primary of T1 whenever the circuit is completed through armature 77 and contact 78. The resultant output signal of T1 is a close approximation of a square wave with a magnitude proportional to the error voltage between 75 and 76. Over-temperatures cause current flow through the primary of T1 in one direction up and under-temperatures cause flow in the opposite direction down, which results in a signal phase reversal. For example, if it is assumed that the chopper K1 and transformer T1 are connected to give a signal voltage at the secondary of T1 in phase with the 400 cycle supply voltage for temperatures above the calibration temperature, then the signal voltage will be 180° out of phase with the supply voltage for under-temperatures. The capacitor C7A produces a leading current which cancels the mechanical and inductive lag of the chopper to permit the signal to be in the desired phase relationship with the supply voltage.

A first stage amplifier and mixer circuit provides for the high amplification of the error signal and the insertion of a signal which represents the rate of temperature change; it includes a triode section of amplifier tube V1, amplifier tube V6 and potentiometer 81. The error signal is amplified by the one triode section of V1 and its associated resistors R6 and R15. Only the amplified signal appears across R17 since the direct current is blocked by capacitor C2. The temperature rate signal is added to the error signal at resistor R3, which is common to the amplifier circuits of both V1 and V6. R15 and R49 are large cathode resistors which produce sufficient individual stage degenerative feedback to permit tube interchangeability and plus or minus variation of about ten percent in the heater voltages with negligible amplifier gain variation. Resistor R2 and capacitor C1A comprise a decoupling filter network for reducing the power supply ripple across the V1 and V6 amplifier stages and minimizing regenerative feedback from the output stages.

A second stage amplifier and mixer circuit provides for the high amplification of the combined error signal and temperature rate signal with the correction rate signal; it includes the second section of tube V1, amplifier tube V4 and associated resistors including adjustable resistor or potentiometer R34, the latter permitting adjustment of the correction rate signal magnitude. The circuit is so designed as to permit such adjustment without affecting the amplification of the error and error rate signals. The resistors R13, R14 and R33 limit the grid current drawn during the positive-going portion of large signals to prevent tube damage.

The combined error, the temperature rate, and correction rate signals are further amplified by circuitry including tube V2 and push-pull transformer T2, the latter having its primary capacitively coupled to V2 and its secondary connected to the grids of both sections of the driving tube V3 to provide push-pull signals, that is, signal voltages 180° out of phase with one another.

The phase sensitive circuit and magnetic amplifier T3 comprises the tube V3, and associated capacitors C5A and C5B; its purpose is to convert the low power signal voltage of the signal amplifier circuit to a voltage with adequate power to energize one phase winding, the variable phase 70, of the servo motor 39. The other phase winding 71 is supplied with a fixed voltage through capacitor C6, which shifts the motor voltage approximately 90° to the supply voltage. The direction of rotation and torque of the two-phase servo motor, which has identical windings, are determined by the voltages applied to the windings and the phase relationship between the two applied voltages. With the voltages to the winding 70 constant, the supply to the other controls the torque and direction of motor rotation. The control voltage is proportional to the error voltage within the saturation limits of the amplifier, and the phase relationship to the supply voltage is determined by the polarity of the error voltage. The output tube V3 is biased by the potential divider circuit which includes resistors R11 and R20 connected to the 255 volt regulated D.C. line. The signal output of transformer T2 must tend to change the voltage on one of the grids of V3 in a positive direction at the same instant that the plate voltage is positive to increase conduction in that tube section. If the temperature sensed by the tailpipe thermocouples is exactly equal to the calibration of the unit, there will be no amplifier signal and both sections of V3 will conduct equal currents. Let it be assumed that the secondary T5C of magnetic amplifier T3 is connected to produce positive plate voltages on section V3A of tube V3 during the period the grid voltage of the same section is going positive on an overtemperature signal (thermocouple temperatures greater than calibration temperature).

Under these conditions, section V3A will conduct a greater average direct current through winding T3A than V3B conducts through T3D, and with under-temperature signals, section V3B will conduct a greater average direct current through winding T3D than V3A conducts through T3A. The magnetic amplifier T3 is represented schematically by six windings on two cores; its operation may be explained on the basis of two transformers having primary windings T3B, T3E, secondary windings T3C, T3F, and control windings T3A, T3D. The two secondary windings are connected series bucking to the variable phase winding 71 of the servo motor 39. With no direct current or equal currents through the control windings T3A, T3D, the 115 volt supply is divided equally across the primary windings T3B, T3E, the secondary voltages cancel each other and the variable phase winding 71 has no applied voltage. Upon the occurrence of an overtemperature condition, the conduction of a greater average direct current through the control winding T3A than T3D will reduce the primary impedance of T3B below that of T3E. Since the 115 volt supply is divided between the two transformer primaries T3B, T3E in direct proportion to their primary impedances, the secondary voltage developed in T3F will exceed the voltage developed in T3C and the resulting difference is applied to the variable phase winding 71 of motor 39. In a similar manner, an under-temperature condition produces a control voltage, but the latter will be 180° out of phase with the overtemperature voltage. The 180° phase reversal in the voltage applied to the variable phase winding reverses the motor torque.

The temperature rate circuit is designed to produce an A.C. signal with an amplitude proportional to the rate of change of the temperature signal, it includes transformer T4 to which is applied the thermocouple voltage modulated by chopper K1, first section of amplifier tube V4, cathode follower in the first section of tube V5, rectifier section in the second section of tube V5, two-section filter network including C11, R40, C12A, R41 and C12B, rate-sensitive circuit C13, R43 and R48, and mechanical modulator or chopper K3. The A.C. signal is conducted to the first section of V4 from the secondary of T4, where it is amplified and then the amplified signal rectified by the second half of V5. The rectified signal is then filtered by C11, R40, C12A, R41, C12B. The filtered D.C. voltage across R42 will vary in magnitude in approximately direct proportion to tailpipe temperature. The first section of V5 functions as a cathode follower which provides the required low impedance source for the rectifier at a signal level nearly equal to that in the high impedance amplifier circuit of V4. The intermediate (rectifying and filtering) step to an A.C. signal permits stable amplification at a high level without power supply variation effects on the rate signal. The rate-sensitive circuit (C13, R43 and R48) output, which is approximately proportional to the rate of change in the D.C. voltage across R42 is modulated by chopper K3, which shorts out R48 at the line frequency. The resultant A.C. signal is added to the error signal in tube V1 through the mixing action of resistor R3.

A small rate generator 82 is connected to the shaft of the motor 39 and provides a 400 cycle correction rate signal which is fed back into the mixer amplifier tube V1 through capacitor C8, potentiometer R34, R33, the second section of tube V4, R8 and R7. The field winding of the generator is supplied with excitation voltage from the 115 volt, 400 cycle input. The generated voltage is directly proportional to the R.P.M. of the actuator motor 39, and its phase relationship to the excitation voltage is a function of the direction of motor rotation. In actual practice, the generator 82 is enclosed within the case of the actuator motor and would not be visible in Figure 2. The correction rate signal feedback into the amplifier slows down the correcting action of the actuator bullet or valve 16 of Figure 2 as the tailpipe temperature approaches the calibration temperature of the amplifier and minimizes control correction overshoot; its action is analogous to that of a dashpot in that it achieves control stability by reducing the control's correction speed without affecting the sensitivity or actuating forces of the control under stall conditions.

A speed switch and relay circuit is indicated at 85; it includes an engine driven speed switch 86, which is shown in the form of a governor 86' adapted to separate a pair of spring-pressed contacts 87 and 88 when the engine speed attains a predetermined value. Also, in the circuit 85 is an arming relay K2, provided with an armature 89, which is connected to a switch 90. As shown, switch 90 is of the normally closed type, that is, it is urged into engagement with a contact 91 by a spring 92 when the relay coil is unenergized; and when said coil is energized, switch 90 is moved into engagement with a contact 93. With switch 90 in engagement with contact 91 (engine speeds in excess of a predetermined value), the variable phase winding 71 of motor 39 is connected to the secondaries T3F and T3C of the magnetic amplifier T3. When switch 90 is in engagement with contact 93 (engine speeds below a predetermined value), the said variable phase winding 71 is connected to the 115 volt supply. The manner in which these respective switch positions affect the operation of the system will be explained in the description of operation, which follows:

Operation

It is assumed that the control is to be used with a fuel feed device having an all-speed governor-type fuel or throttle valve which will automatically maintain a steady engine speed for a given throttle or power lever setting. The curve chart of Figure 6 further assumes that the fuel head across the throttle valve metering restriction is automatically regulated as a function of engine speed, as in the Mock application Serial No. 156,980, heretofore noted.

With reference to Figures 1, 2 and 3, the power lever 18 is at a part-throttle setting (throttle position between 0° and 52°), the throttle cam 52 of Figure 2 is in its ineffective range of movement with respect to follower rod 51, the bullet valve 16 is set for maximum jet area, and speed switch 86 is closed so that relay switch 90 is against contact 93 and the voltages supplied to the field windings 70 and 71 of the actuator motor 39 are in such a phase relationship as will hold the one end of the stop arm 42 against the overtemperature stop 44. Also, the cam 37 is holding the servo valve pistons 30 and 31 in their extreme left hand positions so that annular recesses 32 and 33 are open and high pressure fluid or oil is being vented to that side (bottom side in Figure 2 or right hand side in Figure 1) of the actuator piston 25, which is effective to hold the bullet valve 16 in its maximum area position. This is the "unarmed" position of cam 37.

If now the pilot should move the power lever 18 from part-throttle to maximum power position (90° position) to accelerate from point A to G in Figure 6, the all-speed fuel governor spring (not shown) would be reset and the throttle valve would begin to open. With an exhaust jet area as at M (maximum opening), it requires only a relatively slight increase in the fuel feed rate to accelerate from A to a point beyond the surge area, since the drop across the turbine is at a maximum.

With the throttle or power lever 18 set at maximum power position, the speed switch 86 open, and engine temperature below a predetermined safe value, cam 37 rotates to the position shown in dottled lines in Figure 2 and arm 42 engages the under-temperature stop 43. Throttle cam 52 will have been rotated clockwise and will, under these conditions, be effective to move servo valve pistons 30 and 31 to the right and vent high pressure fluid or oil to the area-reducing side (top side in Figure 2 or left hand side in Figure 1) of the actuator piston 25' by way of port 35 and oil line 26. The bullet valve 16 will

then move to the minimum area or maximum thrust position at G. This reduction in area of the exhaust jet decreases the drop across the turbine (back pressure rise), and were it not for the all-speed governor action on the fuel valve, the engine would slow down. However, the governor now calls for a sharp increase in fuel to maintain the speed selected by the setting of the power lever 18, and the acceleration fuel increase to approximately the maximum temperature limit, viz., a temperature which may be maintained only temporarily or just during acceleration, and follows the maximum temperature line to where governor cut-off begins, whereupon it decreases to steady-speed operating point G.

The pilot is at liberty to reset the throttle or power control lever from idle or low power to maximum power position (90° position) suddenly or in one motion without danger of bringing about an overtemperature condition. This is so, since in order for the bullet valve 16 to close (*a*) the speed switch 86 must be open, and (*b*) the turbine temperature must be below a predetermined safe value. As the throttle or power lever 18 moves through the 93° position, cam 52 acts through rod 51 and lever 48 to move cam 37 to the right, but if the speed switch is closed, cam 37 will remain in its full-line position and will have moved valve pistons 30 and 31 to the left a distance such that the cam 52 becomes ineffective to move said pistons sufficiently far to the right to open port 35 to high pressure oil or fluid. As long as the speed switch remains closed, the variable phase winding 71 is energized by 400 cycle supply voltage and the phase relationship between windings 70 and 71 is such as will cause the motor to rotate the contact end 42' of arm 42 against the overtemperature stop 44 (solid line position of cam 37), at which point the motor stalls. When the speed switch opens, the variable phase winding 71 is energized through the amplifier. If, for example, the engine temperature is at 1255° F., which will be presumed to be the maximum continuous engine operating temperature, the motor torque is such as to just balance out the opposed force of spring 41 and the contact end 42' of arm 42 remains against stop 43, but if the temperature rises above 1255° F., the amplifier puts out a signal to the variable phase winding which is proportional to the degree and rate of temperature rise, and the motor 39 rotates cam 37 to some intermediate position, thereby moving servo valve pistons 30 and 31 to the left and causing hydraulic motor piston 25' to move upwardly and increase the exhaust jet area. As the area increases, two things happen simultaneously: the follow-up mechanism, including worm 61 and shaft 62, starts to recenter the valve pistons 30 and 31 and the temperature drop reduces the voltage to the motor 39, causing the motor cam 37 to rotate such that it also starts to recenter the valve pistons. As long as the overtemperature condition exists, the nozzle area increases until an area is reached where the turbine temperature is 1255° F. When this temperature is reached, the amplifier output is reduced, the pilot valve pistons have centered, movement of power piston 25' has stopped, and the jet nozzle area arrived at is maintained.

Resuming the description of operation in conjunction with Figure 6, as the speed of the engine increases to the point indicated by the vertical line 94, speed switch 86 opens, the relay coil of K2, Figure 3, is de-energized and spring 92 moves switch 90 into engagement with contact 91. The amplifier now supplies voltages in such phase relationship to the field windings 70 and 71 of motor 39 as will cause the motor to rotate arm 42, Figure 2, against the under-temperature stop 43. The actuator is now "armed" and the pilot has complete control of bullet valve position by moving lever 18 within a range of say, 52° to 90°, subject, however, to being overridden by the temperature responsive amplifier in the event of a rise in turbine or tailpipe temperature above a predetermined value with the bullet valve in a partially closed position. This upper temperature limit is the calibration or set temperature of the amplifier, and should this be exceeded, the field windings of motor 39 will be supplied with voltages in such phase relationship as will cause the motor armature or shaft 42 to rotate clockwise, rotating cam 37 in a direction to move servo valve pistons to the left and vent high pressure fluid to the underside of actuator piston 25' and venting the opposite side thereof to drain. The exhaust jet area will then be increased until the turbine or tailpipe temperature equals the amplifier set temperature. A rise in turbine or tailpipe temperature (more briefly expressed as engine temperature) at a given setting of the pilot's control lever may result from changes in altitude, ambient air temperature and other factors varying with engines having different characteristics. When the bullet valve 16 reaches any one of its given positions, the follow-up cam 58 of Figure 2 will have centered or balanced the servo valve pistons 30 and 31, and power piston 25' will then be held against further movement until the pilot valve pistons are again displaced through rotation or axial movement of cam 37.

Assume the engine is operating at a speed below that required to close switch 19'' when the throttle is rotated into the after burner range position, which lies between 93° to 110°. The afterburner control device 17'' will be actuated via the linkage 21' but fuel cannot be fed to the afterburner manifold at this time because the normally closed solenoid valve 19' remains closed until energized by the closing of the switch 19''. If the engine is operating at the speed setting of the switch 19'' when rotation of the throttle 18 into the afterburner range, 93° to 110°, occurs, the afterburner control device 17'' is actuated as above noted, except that now the solenoid valve 19' is open to allow additional fuel to be supplied to the engine via the manifold 17'''.

Since the face 52' of the cam 52 has a constant radius, rotation of the throttle 18, from 93° to 110° will not effect movement of the follower rod 51. That is, where cam 52, of Figure 2, is used there will be no manual control of the exhaust area opening in the afterburner range of the engine; the servo valve 28 will be under the sole control of the electronic engine temperature sensing system at this time. However, with the use of cam 52'', Figure 2*a*, the pilot continues to exercise control over the exhaust area opening in the afterburner range subject to further control by the electronic engine temperature sensing system.

Should the pilot decelerate as indicated by the dotted arrow line in Figure 6, cam 52 will be rotated counterclockwise back to the position shown in Figure 2 and the spring-pressed follower rod 51 will move to the left, causing servo valve 28 to move power piston 25' in a direction to retract the bullet valve 16.

Should there be an electrical power failure, the spring 41 will cause the end 42' of arm 42 to engages the under temperature stop 43 and move cam 37 to the dotted line position. This action will cause the pilot or servo valve pistons to move to the right such distance as will open the upper side of power piston 25' to pressure and the lower side to drain, and effect a reduction in exhaust jet area to a point where full engine thrust or power may be developed through operation of the pilot's control lever, or by variation in the rate of fuel feed.

To summarize the operation:

(*a*) At engine speeds below speed switch setting, speed switch 86 is closed, switch 90 of relay K2 is against contact 92 and the motor 39 is energized by a fixed phase voltage and the 400 cycle supply voltage. This causes the motor to rotate stop arm 42 with the end 42' thereof against overtemperature stop 44. Motor cam 37 is then in the full line position, holding pilot valve 28 open so that pressure fluid is vented to the rod side of power piston 25' and the bullet valve 16 fully retracted (maximum jet area). These conditions are maintained for power

lever positions from say zero to 52°, although, as heretofore noted, during acceleration the power lever can be moved to full thrust position and the speed switch will still remain closed until the speed attains a predetermined value.

(*b*) At engine speeds above setting of switch **86** and power lever positions above 52°, the said switch opens and the variable phase of motor **39** is energized through the amplifier of Figure 3. If engine temperature is at the upper limit, the motor produces sufficient torque to just balance out the force of spring **41**, but not enough to move the end **42'** to stop arm **42** away from undertemperature stop **43**. If engine temperature is below the upper limit (amplifier set temperature), the motor cam **37** turns to the dotted line position with the end **42'** of arm **42** against undertemperature stop **43**, throttle cam **52** has caused pilot valve **28** to open the hydraulic pressure line **26** to the upper side of power piston **25'**, and bullet valve **16** moves toward closed or minimum jet area position. As said valve **16** moves in its area decreasing direction, it acts through follow-up shaft **62**, cam **58** and rod **59**, to return pilot valve pistons **30** and **31** to centered position when the selected nozzle area is reached.

(*c*) Should the engine temperature exceed the set temperature (1255° Fahrenheit), the amplifier puts out a signal to the variable phase winding **71** of motor **39** which is approximately proportional to the combined error signal, correction rate signal, and temperature rate signal; whereupon said motor rotates cam **37** to some intermediate position, followed by movement of pilot valve pistons **30** and **31** to the left and retraction of bullet valve **16**. As bullet valve **16** retracts, follow-up cam **58** starts to recenter the servo valve pistons and the drop in temperature resulting from an increase in jet area reduces the voltage to motor **39**, whereupon motor cam **37** is rotated in a direction such that it also starts to recenter the said servo valve pistons. As long as an overtemperature condition exists, jet nozzle area will increase until an area is reached where the engine temperature equals the amplifier set temperature. When this temperature is reached, pilot valve pistons **30** and **31** will have centered and further movement of power piston **25'** is stopped.

Although only one embodiment of the invention has been illustrated and described, various changes in form and relative arrangement of parts may be made to suit requirements.

We claim:

1. In a fuel feed and power control system for a turbojet engine having an exhaust jet, valve means for varying the effective area of the jet, a hydraulic actuator for said valve means, a servo valve for said actuator, fuel feed regulating means including a main fuel control and an afterburner control, a power control member connected to said main and afterburner controls and movable between minimum and maximum power settings and between the latter and a maximum thrust augmentation setting, means operatively connecting said member to said servo valve in a manner such that over a range of movement of said member between a minimum power setting up to a given intermediate power setting the servo valve holds a position which causes the actuator to maintain the area of the jet substantially maximum, movement of said member from the intermediate setting to a substantially maximum power setting is effective through said last mentioned means to adjust the servo valve to cause the actuator to move the valve means in a direction to reduce the area of the jet, and movement of said member from said maximum power setting to a thrust augmentation setting is effective through said last mentioned means to adjust the servo valve to cause the actuator to move the valve means in a direction to increase the area of the jet, said power control member being so arranged that movement of said member between minimum and maximum power settings coordinates fuel flow from the main fuel control with jet area, movement of said member between maximum power setting and a maximum thrust augmentation setting coordinates fuel flow from the afterburner fuel control with jet area, an electric servo motor also operatively connected to said servo valve for adjusting the latter and arranged to override control of the servo valve by said member, an electric circuit for energizing said servo motor including a device for establishing a signal representing deviations in temperature from a given engine temperature, the circuit arrangement being such that at engine temperatures below said given value the servo motor is ineffective to override control of the servo valve by said member but at temperatures above said given value the servo motor overrides such control and becomes effective to adjust the servo valve in a direction to produce an increase in the area of the jet.

2. A fuel feed and power control system as claimed in claim 1 wherein said circuit is provided with means responsive to engine speeds below a predetermined value to cause said servo motor to adjust said control device to produce a minimum jet area, and means responsive to engine speed beyond said predetermined value for connecting the servo motor so that it responds to overtemperature signals.

3. In a fuel feed and power control system for a turbojet engine having an exhaust jet, valve means for varying the effective area of the jet, a power actuator for said valve means and an adjustable control device for said actuator, fuel feed regulating means including a main fuel control and an afterburner control, a power control member connected to said main and afterburner controls and movable between minimum and maximum power settings and between the latter and a maximum thrust augmentation setting, means operatively connecting said member to said control device in a manner such that over a range of movement of said member between a minimum power setting up to a given intermediate power setting the effective jet area is maintained substantially maximum, movement of said member from the intermediate setting to a substantially maximum power setting is effective to adjust said control device to cause the actuator to move said valve means in a direction to reduce the area of the jet, and movement of said member from the maximum power setting to a thrust augmentation setting is effective to establish a predetermined jet area, said power control member being so arranged that movement of said member from minimum to maximum power setting is effective to operate said main fuel control, movement of said member from maximum power setting to a thrust augmentation setting is effective to operate said afterburner fuel control, an electric servo motor also operatively connected to said control device for adjusting the latter to thereby override control by said member, an electric circuit for energizing said servo motor including a device for establishing a signal representing deviations in temperature from a given engine temperature, the circuit arrangement being such that at engine temperatures below said given value the servo motor is ineffective to override control by said member but at temperatures above said given value said servo motor overrides control by said member and becomes effective to adjust said control device in a direction to produce an increase in the area of the jet whether the power control member is set for maximum power or thrust augmentation.

4. In a power control system for a turbojet engine having an exhaust jet and an afterburner, valve means for varying the effective area of the jet, a hydraulic actuator for said valve means, a servo valve for said actuator, a fuel control device for said afterburner, a power control member movable between minimum and maximum power positions, means operatively connecting said member to said servo valve and said fuel control device such that over a range of movement of said

member between a minimum power setting up to a given higher power setting the servo valve positions the actuator to maintain a scheduled maximum jet area and from such given higher setting to a setting corresponding to maximum non-afterburning power setting said member becomes effective to adjust the servo valve to cause the actuator to move the valve means in a direction to reduce the area of the jet, and during the afterburner range of operation said member is connected to control fuel flow to said afterburner as a function of the position of said member and to control said actuator such that the effective area of the jet is maintained at a minimum, an electric servo motor, means operatively connecting said servo motor to said servo valve for adjusting the latter including means for overriding control of the servo valve by said member, and electrical means for energizing said servo motor including a device for establishing a signal representing deviations in engine temperature from a predetermined value wherein signals indicating engine temperatures below said predetermined value render said servo motor ineffective to override control of the servo valve by said member and signals indicating temperatures above such a value render a servo motor effective to override such control and adjust the servo valve in a direction to produce an increase in the area of the jet, and means for rendering said override means operate at engine speeds above a predetermined value.

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