

[54] FUEL CONTROL FOR TURBINE TYPE
POWER PLANT HAVING VARIABLE AREA
GEOMETRY

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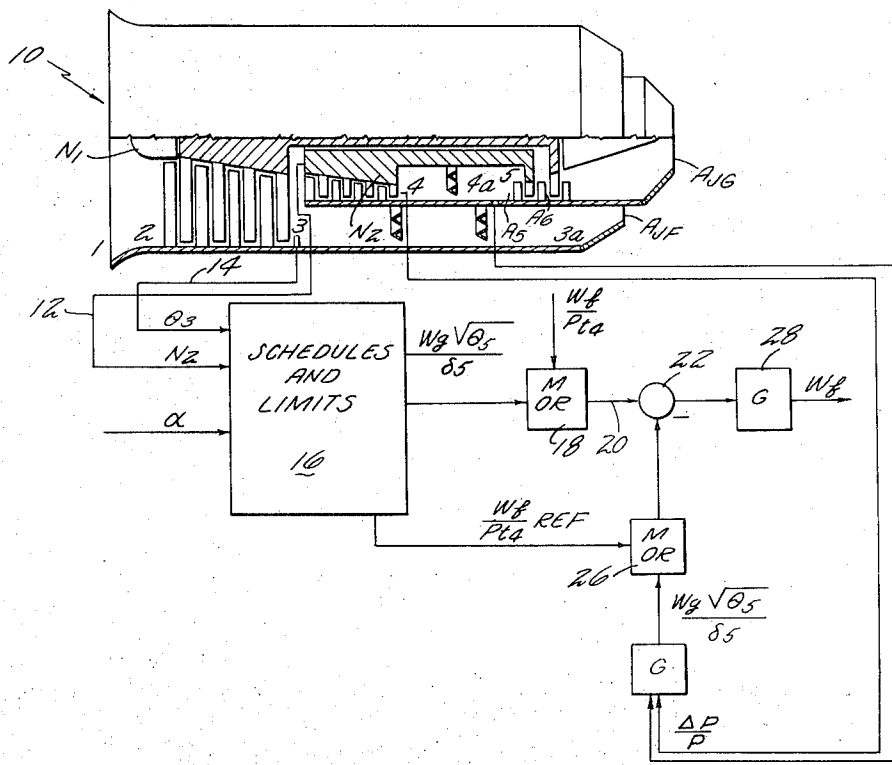
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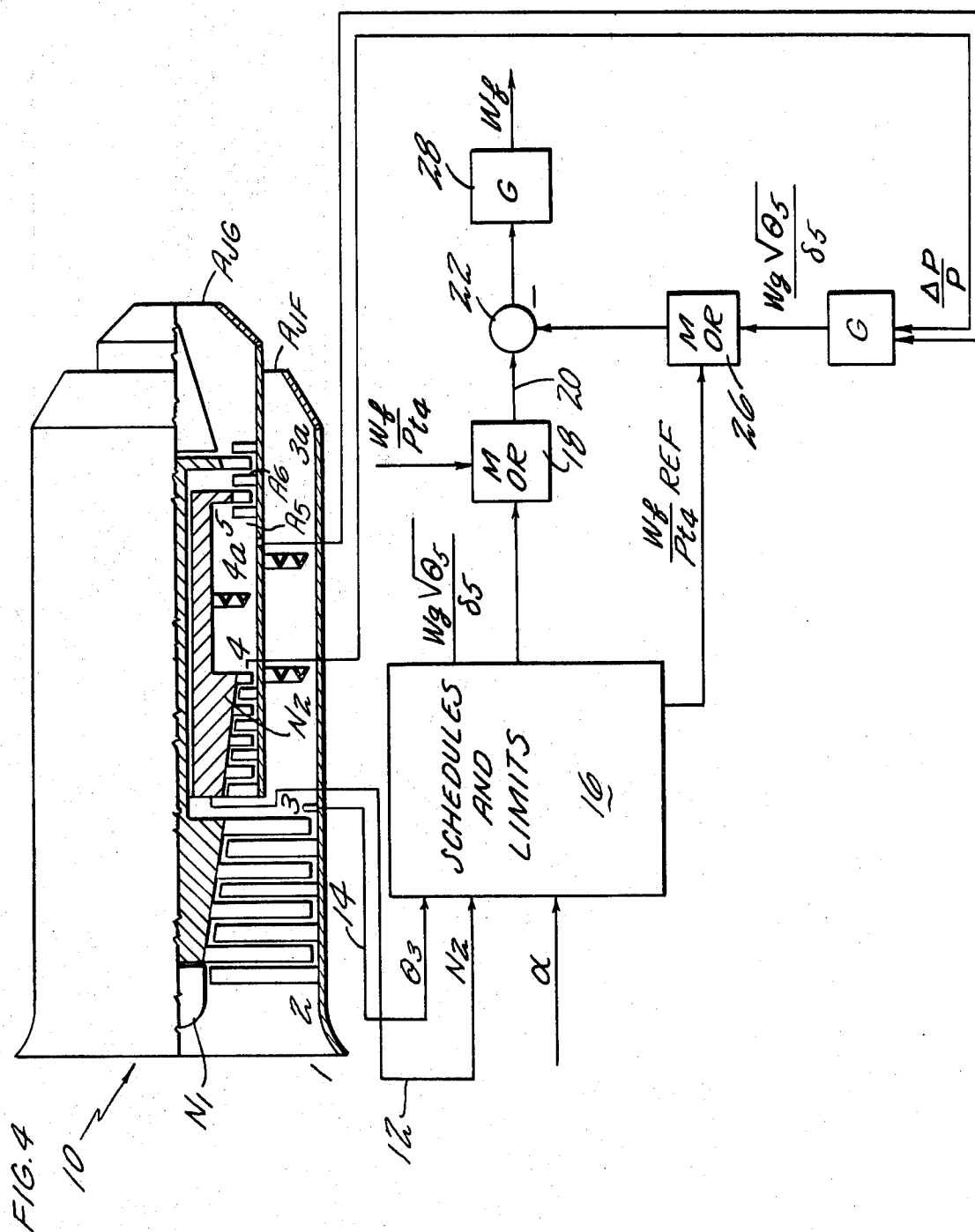
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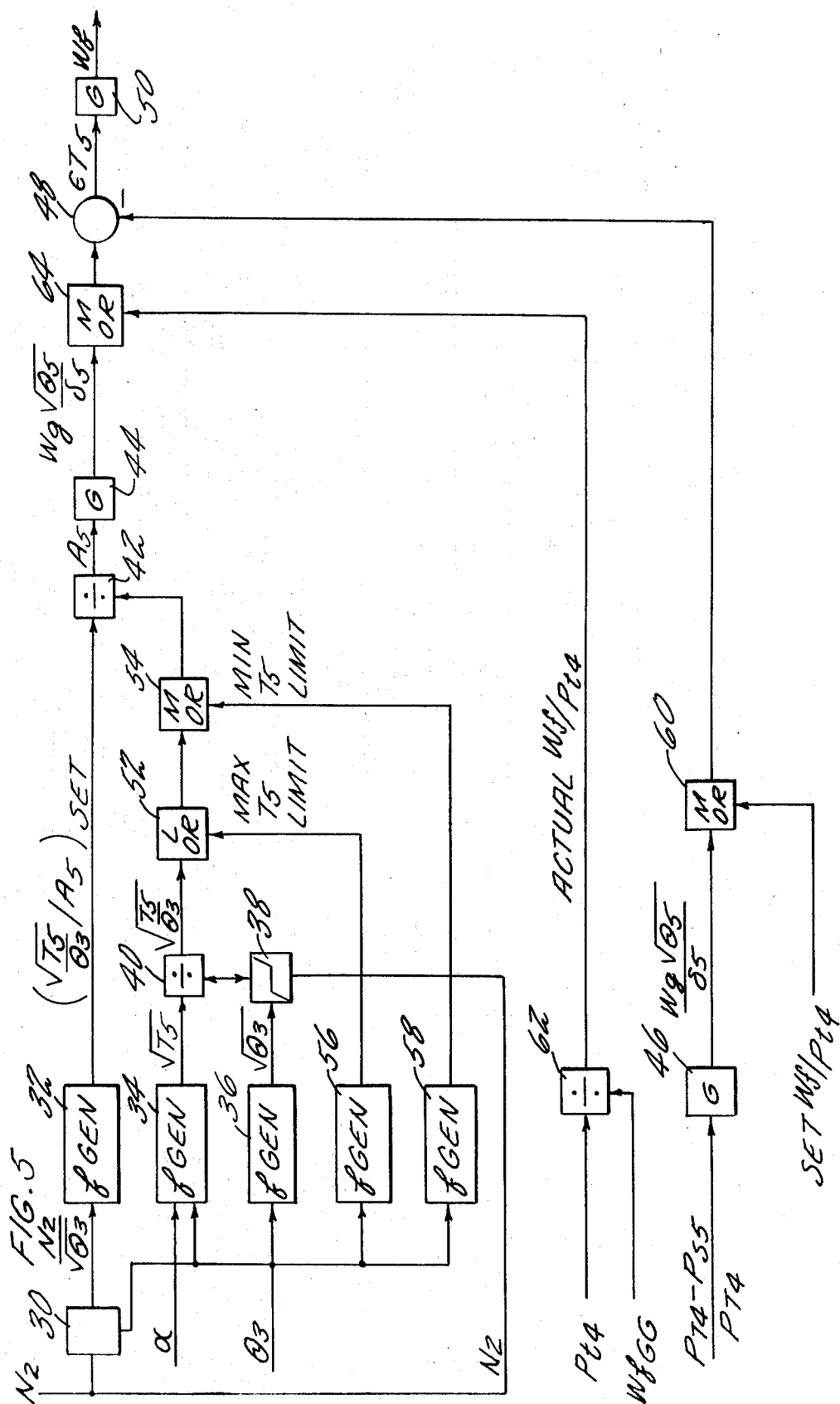
[57] ABSTRACT

The turbine inlet temperature of a turbine type of power plant, particularly the type that includes a variable geometry, is controlled by setting a referred weight flow of the power plant working medium and closing the loop through fuel flow so that the actual referred weight flow matches the set value. The ratio of the difference between the total pressure upstream of the burner and the static pressure downstream of the burner to the total pressure upstream of the burner serves to produce a signal indicative of the actual weight flow of the power plant working medium.

7 Claims, 5 Drawing Figures







FUEL CONTROL FOR TURBINE TYPE POWER PLANT HAVING VARIABLE AREA GEOMETRY

BACKGROUND OF THE INVENTION

This invention relates to fuel controls for a turbine type of power plant and particularly to a fuel control which schedules a $\Delta P/P$ (all symbols are listed hereinbelow) and adjusts fuel flow to match this value.

As is well understood the fuel control serves to control the operation of a jet engine by monitoring certain engine operating parameters and computing them into a control parameter which assures that the engine is operating at its most effective operational condition taking into consideration fuel economy, rich and lean blowouts, and the structural integrity of the engine. Obviously, the gas generator turbine inlet temperature (T.I.T.) is primarily controlled by the modulation of the gas generator fuel flow. It is obvious that as turbine inlet temperature is increased thrust is increased and the value of the turbine inlet temperature is designed so that it is maintained below its maximum limit at partial augmentation and is increased to its maximum limit at maximum augmentation. It also follows that the maximum turbine inlet temperature is determined by the turbine actual structural limits although during transients, these limits may exceed the steady state temperature limit.

The turbine inlet temperature may be controlled without the use of temperature sensors measuring the temperature by controlling $\Delta P/P$ in closed loop fashion. As can be shown, $\Delta P/P$ may be expanded mathematically and expressed in terms of its fundamental constituents which are $\left[1 - \frac{P_{s4a}}{P_{t4a}} \left(1 - \frac{\Delta P_b}{P_{t4}}\right)\right]$.

The term $\Delta P_b/P_{t4}$ is the total pressure loss in the burner which varies almost purely as a function of the Mach number leaving the compressor (that is, entering the burner). This Mach number is already used to control the compressor operating point and may be set as a function of power lever and flight conditions. The term P_{s4a}/P_{t4a} is the static-to-total pressure ratio at a point immediately upstream of the turbine nozzles and is purely a function of the Mach number at this point which is a measure of corrected air flow. Further, since the total temperature, pressure and mass flow at this point are identical with that at the turbine nozzle, this Mach number depends only on the turbine nozzle area.

Since the set compressor operating point determines a unique value of $T_5/\theta_3/A_5$, it can be seen that a given compressor operating point set by power lever and flight conditions, closing the loop on a scheduled value of the specified $\Delta P/P$ sets a unique value of turbine inlet temperature. Among the advantages of this system are the magnitude of the signal ratio, its gain relationship with turbine inlet temperature, the elimination of any need to precisely measure turbine nozzle area, and the elimination of protruding total pressure pick-up probes in the hot sections of the engine.

SUMMARY OF INVENTION

A primary object of this invention is to provide for a gas turbine variable geometry engine, a fuel control that utilizes a scheduled $\Delta P/P$ parameter, closes the loop on said parameter by varying fuel flow.

A still further object of this invention is to provide a fuel control for a gas turbine variable geometry engine

means for adjusting fuel flow as a function of the difference between scheduled ΔP and actual $\Delta P/P$.

A still further object of this invention is to control turbine inlet temperature of a gas turbine engine without measuring this temperature. A still further object of this invention is to control turbine inlet temperature of a gas turbine engine whose geometry is variable without measuring the area of the variable geometry.

Other features and advantages will be apparent from the specification and claims and from the accompanying drawings while illustrate an embodiment of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a graph illustrating a plot of specific fuel consumption versus thrust or W_a (airflow) for values of compressor pressure ratio and turbine inlet temperature.

FIG. 2 is a graph illustrating a partial compressor map, low

FIG. 3 is a graph of a plot of corrected speed versus low compressor discharge temperature.

FIG. 4 is a schematic illustration showing the basic concept of this invention.

FIG. 5 is a schematic illustration showing in more detail the preferred embodiment of this invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

List of Symbols

$N_1/\sqrt{\theta_2}$	— Referred Low Pressure Rotor Speed
$N_2/\sqrt{\theta_3}$	— Referred High Pressure Rotor Speed
P_{t4}	— High Pressure Compressor Pressure
P_{t3}	— Low Pressure Compressor Pressure
P_{t2}	— Engine Inlet Pressure
F_{g0}	— Gas Generator Thrust
F_d	— Duct Thrust
K	— Ratio of specific heats
F_n	— Engine Net Thrust
W_a	— Air Flow
θ_i etc.	— Station Total Temperature Ratio to NACA Standard Day Temperature
Γ_{t3} etc.	— Station Total Pressure Ratio to NACA Standard Day Pressure
T_t	— Total Temperature (Rankine)
P_t	— Total Pressure (Psia)
P_s	— Static Pressure (Psia)
$W_a\sqrt{\theta_4/84}$	— Referred Gas Generator Compressor Discharged Air Flow
ΔP	— $P_t - P_s$
M	— MACH Number
ϵ	— Any of Several Constants
C	— Influence Coefficient
T_d	— Duct Total Temperature at 3a
N_1	— Low Pressure Rotor Speed
Γ	— is a referred flow parameter
W_g	— $W_a + W_f$ or total mass flow
W_f	— Fuel Flow
N_2	— High Pressure Rotor Speed
A_5	— N_2 Turbine Inlet Area
A_6	— N_1 Turbine Inlet Area
A_{JF}	— Duct Exhaust Nozzle Area
A_{JG}	— Gas Generator Exhaust Nozzle Area
Subscripts 1 to 6	— Indicate Engine Stations

The immediate portion of this specification is intended to provide a background to and a development of the utilization of $\Delta P/P$ as a valid control parameter

for a gas turbine engine whose geometry is variable.

Thrust (F_n) can be expressed as follows:

$$F_n = f(Wa, \text{T.I.T.})$$

In order to maximize F_n for any gas turbine (fixed or variable geometry) both the Wa and T.I.T. must be at their maximum value, it being noted that Wa is directly related to compressor (N) for any given flight condition. This is illustrated in the graph of FIG. 1 where the family of curves bearing reference letter A indicates different T.I.T. values. Since F_n/Wa increases as T.I.T. increases, then for any given maximized airflow, Wa ,

$$\text{since: } F_n = F_n/Wa \times Wa$$

as T.I.T. increases,

F_n increases.

In addition, another consideration for turbine engines is that it should operate at optimum specific fuel consumption (SFC). SFC decreases as compressor pressure ratio increases so that the fuel control must operate to maintain the compressor pressure ratio as high as possible.

As is apparent from the foregoing, the T.I.T. and compressor pressure ratio must operate at their highest value within the realm of the structural and integrity of the engine.

Referring to the compressor map illustrated in FIG. 2, it will be also appreciated that the fuel control must prevent $N/\sqrt{\theta_3}$ and P_4/P_3 from reaching values that would put the compressor in surge, illustrated by line C, i.e., any condition above line C would result in surge.

It will be noted from FIG. 2 that the steady state line D for a given compressor inlet pressure (cip) value remains fixed in a fixed geometry gas turbine. However, the steady state line E can be made to shift by varying the geometry of the engine. Additionally, as illustrated by curve F (FIG. 3) for a constant maximum N, $N/\sqrt{\theta_3}$ decreases as the aircraft Mach No. increases. Transposing points G, H, and I, from FIG. 3 to the compressor map will establish the steady state operating line E for a given scheduled area of the variable geometry engine. (This line varies as geometry varies.)

Since corrected flow entering the turbine stator is in the choked condition, $Wa \sqrt{T_5/A_5 P_5}$ will remain at a constant value.

This equation can be expanded algebraically as follows:

$$\frac{Wa \sqrt{\theta_3}}{\delta_3} \sqrt{T_5/\theta_3} = A_5 P_5 / \delta_3$$

Lines K of values of $\sqrt{T_5/\theta_3}/A_5$ are superimposed on the compressor map (FIG. 2) showing that for a given operating point determined by $N/\sqrt{\theta_3}$, and the desired separation from surge, the value of $\sqrt{T_5/\theta_3}/A_5$ can be established.

Therefore, $\sqrt{T_5/\theta_3}/A_5$ is uniquely determined and set by setting the compressor operating point. (For example, points G, H, and I of FIG. 2.)

As will be explained hereinbelow $\Delta P/P$ is directly related to A_5 ; thus setting $\Delta P/P$ also sets A_5 .

Since A_5 and $\sqrt{T_5/\theta_3}/A_5$ are set as was explained hereinabove, in accordance with this invention, the fuel control serves to obtain the maximum T_5 by scheduling $\Delta P/P$ so as to obtain the optimum SFC and maintain the

operating conditions within the thermal and structural integrity of the engine while assuring that surge does not ensue.

To further appreciate the efficacy of $\Delta P/P$ as a control parameter, the following mathematical equations are presented.

$$\Delta P/P = P_{t4} - P_{s4a}/P_{t4} = 1 - P_{s4a}/P_{t4a} (1 - \Delta P_b/P_{t4}) = 1 - P_{s4a}/P_{t4a} (1 - (P_{t4} - P_{t4a})/P_{t4})$$

$$\frac{\partial \Delta P}{\Delta P} = \frac{\frac{\partial \Delta P}{P}}{\frac{\Delta P}{P}} = \frac{\frac{\partial \Delta P}{P}}{\frac{\Delta P}{P}} + \frac{\frac{\partial \Delta P_b}{P}}{\frac{\Delta P_b}{P}} \cdot \frac{\frac{\partial P_{t4}}{P_{t4}}}{\frac{\Delta P_b}{P_{t4}}}$$

For flow in an enclosed channel, such as a burner, the ratio of static to total pressures at any point depends primarily on the local Mach number.

Therefore $P_{s4a}/P_{t4a} = f(M_{4a})$ only

When the turbine is choked, from flow continuity

$$M_{4a}/M_5 = f(A_5/A_{4a}) \text{ only}$$

Since $M_5 = \phi$ regardless of value of A_5 and $A_{4a} \phi$

then M_{4a} and $P_{s4a}/P_{t4a} = f(A_5/A_{4a})$ only for main burner

$$\Delta P_b/P_{t4} = F(M_{4a}^2) \text{ primarily}$$

Assume a given compressor operating point at any given operating point

$$N/\sqrt{\theta}, P_4/P_3, Wa, \sqrt{\theta_4}/4, M_4 \text{ are all constant}$$

$$\begin{aligned} \therefore \frac{\partial \Delta P}{\Delta P} &= \frac{\frac{\partial \Delta P}{P}}{\frac{\Delta P}{P}} = \frac{\frac{\partial \Delta P}{P}}{\frac{\Delta P}{P}} + \frac{\frac{\partial P_{s4a}}{P_{t4a}}}{\frac{P_{s4a}}{P_{t4a}}} \cdot \frac{\frac{\partial P_{t4}}{P_{t4}}}{\frac{P_{s4a}}{P_{t4a}}} \\ &= \frac{-1}{\frac{P_{t4}}{P_{s4a}} - 1} \cdot \frac{\frac{\partial P_{s4a}}{P_{t4a}}}{\frac{P_{s4a}}{P_{t4a}}} \end{aligned}$$

also $W \sqrt{T_5/P_{t5}} = \phi A_5 = \Gamma_5$ (choked flow) and $W \sqrt{T_{t4a}/P_{t4a}} = A_{49} \sqrt{gK/R} M_{4a} [1 + K - 1/2 M_{4a}^2] K + 1/2(1 - K) = \Gamma_{4a}$ (unchoked flow)

but $T_{t4a} = T_{t5}$ } combustion completed
and $P_{t4a} = P_{t5}$ } no further losses

$$\therefore \Gamma_{4a} = \Gamma_5$$

$$\text{Since } \delta \Gamma_5 / \Gamma_5 = \delta A_5 / A_5 = \delta \Gamma_{4a} / \Gamma_{4a}$$

$$\text{and } \delta \Gamma_{4a} / \Gamma_{4a} = [1 - M_{4a}^2 / 1 + (K - 1/2) M_{4a}^2] \delta M_{4a} / M_{4a}$$

$$\text{then } \delta M_{4a} / M_{4a} = [1 + (K - 1/2) M_{4a}^2 / 1 - M_{4a}^2] \delta A_5 / A_5$$

$$\text{also } P_{t4a} / P_{s4a} = 1 + K - 1/2 M_{4a}^2 \mid K/K \mid 1$$

or

$$\frac{\partial \frac{Ps4a}{Pt4a}}{\frac{Ps4a}{Pt4a}} = \frac{-KM4a^2}{1 + \frac{K-1}{2}M4a^2} \frac{\partial M4a}{M4a}$$

and

$$\frac{\partial \frac{Ps4a}{Pt4a}}{\frac{Ps4a}{Pt4a}} = \frac{-KM4a^2}{1 - M4a^2} \frac{\partial A5}{A5}$$

Finally

$$\frac{\partial \frac{\Delta P}{P}}{\frac{\Delta P}{P}} = \frac{1}{\left(\frac{Pt4a}{Ps4a}\right) - 1} \cdot \frac{KM4a^2}{1 - M4a^2} \frac{\partial A5}{A5}$$

Since at any given operating point $T5/A5 = \delta$

$$\delta A5/A5 = 1/2 \delta T5/T5$$

then

$$\frac{\partial \frac{\Delta P}{P}}{\frac{\Delta P}{P}} = \frac{1}{2} \left[\frac{1}{\frac{Pt4a}{Ps4a} - 1} \cdot \frac{KM4a^2}{1 - M4a^2} \frac{\partial T5}{T5} \right]$$

From the foregoing, it is therefore apparent that a change in $\Delta P/P$ parameter is directly related to turbine inlet temperature and thus closing the loop on a scheduled value of the specified $\Delta P/P$ sets a unique value of turbine inlet temperature.

Referring next to FIGS. 4 and 5, a fuel control utilizing this concept will be described hereinbelow by the use of block diagrams. It is to be understood, however, that the fabrication of the control, whether it employs electronics, hydraulics, mechanical means or pneumatics, is a matter of choice and within the contemplation of this invention. Although not limited thereto, a suitable type of fuel control that could be adapted to utilize a concept of this invention is disclosed in U.S. Pat. Nos. 3,307,352 granted on Mar. 7, 1967 and 3,317,134 granted on May 2, 1967.

Referring next to FIG. 4 showing a turbine type of power plant generally illustrated by numeral 10 which in this instance is a twin spool ducted fan bypass engine with variable area exhaust and bypass nozzles. As will be obvious to one skilled in this art it is contemplated within the scope of this invention to utilize any other type of gas turbine engine. However, the type utilized must include a variable area geometry. According to this invention compressor speed is measured by suitable means via line 12 and fan discharge temperature indicated by line 14 is suitably measured and admitted to the computation scheduling and limiting computer generally illustrated by numeral 16. The fan discharge temperature in this instance is converted to a corrected value in any suitable manner so that the schedule computer 16 produces a signal indicative of corrected airflow $W_g \sqrt{\theta_5}/\delta$ 5. This signal is transmitted to the most

OR gate 18 which also receives a signal indicative of W_f/P_{t4} via line 20. This signal is converted in a typical manner as for example as described in U.S. Pat. No. 3,307,352, supra. The higher value of the two signals, that is, $W_g \sqrt{\theta_5}/\delta$ 5 or W_f/P_{t4} is transmitted to the summing point 22. Scheduling computer 16 simultaneously produces a scheduled signal indicative of $W_{f/P_{t4}}$ referenced signal which, in turn, is transmitted to the most OR gate 26. This signal is compared with actual corrected airflow which is obtained by measuring the actual $\Delta P/P$ as was described hereinabove. Thus, whenever the corrected air weight flow drops below the actual W_f/P_{t4} signal, the W_f/P_{t4} signal will be controlling and this signal is then transmitted to the computing box 28 which, in turn, produces a signal indicative of weight flow of the fuel. Whenever the scheduled corrected gas flow is controlling and the corrected gas flow does not match the actual corrected airflow, fuel flow will change so that the two signals will correspond and eliminate any error between the two. Thus, the actual corrected airflow is designed to match the desired corrected airflow.

Referring next to FIG. 5 which is a more detailed description of this invention as shown in the block diagram, in order to assure proper engine operation it is desirable to limit turbine inlet temperature to its maximum and minimum values and also assure that whenever the actual corrected airflow goes below a predetermined value, fuel is controlled by another signal which will eliminate any potential problems associated with manifold filling or with low $\Delta P/P$ signal strength at low engine speeds.

Under normal operation, sensed N_2 and θ_3 serve to generate a scheduled corrected airflow signal $W_g \sqrt{\theta_5}/\delta$ 5 which signal is compared with actual $W_g \sqrt{\theta_5}/\delta$ 5 and adjusts fuel flow until both signals match.

The first portion will describe how the scheduled corrected airflow is obtained. Sensed N_2 and θ_3 are computed in divider 30 to produce an output signal indicative of $N_2/\sqrt{\theta_3}$. The function generator 32 converts that function into a signal indicative of the scheduled $\sqrt{T_5/\theta_3}/A5$.

Simultaneously, power lever position (α) and θ_3 are fed to function generator 34 for producing a signal indicative of $\sqrt{T_5}$, θ_3 to function generator 36 for obtaining a signal indicative of $\sqrt{\theta_3}$ and N_2 is fed to computer 38 so that the combined effect of computer 38 modifies divider 40 to produce an output signal indicative of $\sqrt{T_5/\theta_3}$. This signal is ultimately fed to divider 42 where it produces a signal indicative of $A5$. Since the value of $\sqrt{T_5/\theta_3}/A5$ and θ_3 is known and the desired T_5 is known, it follows that the nozzle are is known.

Since the turbine nozzle runs "choked," i.e., at Mach one airflow where upstream pressure is not affected by downstream pressure, the area signal can be converted through the controller 44 to indicate a set $W_g \sqrt{\theta_5}/\delta$ 5 signal (corrected airflow).

Under normal operating conditions, i.e., whenever corrected airflow is higher than W_f/P_{t4} , scheduled $W_g \sqrt{\theta_5}/\delta$ 5 is compared with actual $W_g \sqrt{\theta_5}/\delta$ 5 to adjust fuel flow to maintain this value at zero error.

The next portion will describe how the actual $W_g \sqrt{\theta_5}/\delta$ 5 signal (corrected airflow) is obtained. As was discussed in the mathematical derivations, $\Delta P/P$ is measured and converted into an actual corrected airflow signal via the computer 46. it is apparent that Δ

P/P can be scheduled and compared with actual to obtain the same results. This signal is transmitted to the summing point 48 which compares the set value with the actual value. The error (indicative of T_5) is then computed by the controller 50 to produce a signal indicative of W_f . As mentioned previously, W_f is adjusted until the actual value matches the set value.

The least OR gate and the more OR gate serve to assure that the turbine inlet temperature does not go below or exceed predetermined values. θ_3 serves to schedule these values through function generators 56 and 58.

It is contemplated that at low compressor speeds the strength of the $\Delta P/P$ signal may be imperceptible so that an alternative method of controlling may be necessary. This will also avoid manifold fuel filling problems that may be occasioned at these low speeds. Accordingly, W_f/P_{t4} is scheduled as a function of $N_2/\sqrt{\theta_3}$ in any suitable manner, as for example as described in U.S. Pat. No. 3,307,352, supra, or any other well-known method. This signal is admitted to the most OR gate 60 so that the higher of the two signals is transmitted to the summer 48.

The actual P_{t4} and W_f are measured and divided by divider 62 to produce the actual W_f/P_{t4} signal which is transmitted to the most OR gate 64. Thus whenever the W_f/P_{t4} signal is higher than the corrected airflow signal, it will control and adjust fuel flow so that the actual value matches the scheduled value.

What has been shown by this invention is that with a given compressor operating point set by power lever and flight conditions, closing the loop on a scheduled value of $\Delta P/P$ sets a unique value of T_5 . Thus, a fuel control embodying this concept affords the following advantages:

1. high magnitude of the signal ratio
2. good gain relationship with turbine inlet temperature
3. the elimination of any need to measure nozzle area, and
4. elimination of temperature sensors in the hot sections of the engine.

It should be understood that the invention is not limited to the particular embodiments shown and described herein, but that various changes and modifications may be made without departing from the spirit or scope of this novel concept as defined by the following claims.

We claim:

1. A fuel control for a gas turbine engine having a variable area turbine inlet geometry such that its steady state operating condition shifts for different area values, said engine having a burner, a compressor and a turbine driven by the hot gases from the burner for driving said compressor,
a source of fuel,
connection means interconnecting said source of fuel and said burner section,
fuel metering means in said connection means for regulating the amount of fuel being delivered to said burners,
and control means for controlling said fuel metering means,
said control means includes means for setting a first signal indicative of $\Delta P/P$, where ΔP = differential between total pressure upstream of the burner and static pressure downstream of the burner, P = total pressure upstream of the burner,
means for measuring and calculating the actual $\Delta P/P$

value of the engine for generating a second signal, and means responsive to said first and second signals for controlling said fuel metering means.

2. A fuel control as claimed in claim 1 including a power lever, said control means being responsive to said power lever and another engine operating variable for setting said first signal.

3. A fuel control as claimed in claim 2 wherein said other engine operating variable is the rotational speed of said compressor.

4. A fuel control as claimed in claim 3 wherein said control means is also responsive to compressor inlet temperature.

5. A fuel control for a gas turbine engine having a variable area turbine inlet geometry such that its steady state operating condition shifts for different area values, said engine having a burner, a compressor and a turbine driven by the hot gases from the burner for driving said compressor,

- a source of fuel,
connection means interconnecting said source of fuel and said burner section,
fuel metering means in said connection means for regulating the amount of fuel being delivered to said burners,
and control means for controlling said fuel metering means,
said control means includes means for setting a first signal indicative of referred compressor discharge air flow,
and means for measuring the actual $\Delta P/P$ value of the engine for generating a second signal, where ΔP = differential between total pressure upstream of the burner and static pressure downstream of the burner, P = total pressure upstream of the burner, and means responsive to said first and second signals for controlling said fuel metering means.

6. A fuel control for a gas turbine engine having a variable area turbine inlet geometry such that its steady state operating condition shifts for different area values, said engine having a burner, a compressor and a turbine driven by the hot gases from the burner for driving said compressor,

- a source of fuel,
connection means interconnecting said source of fuel and said burner section,
fuel metering means in said connection means for regulating the amount of fuel being delivered to said burners,
and control means for controlling said fuel metering means,
said control means includes means for setting a first signal indicative of $\Delta P/P$, where ΔP = differential between total pressure upstream of the burner and static pressure downstream of the burner, P = total pressure upstream of the burner,
and means for measuring the actual $\Delta P/P$ value of the engine for generating a second signal,
means responsive to said first and second signals for controlling said fuel metering means, and
means responsive to another control parameter for controlling said fuel metering means when the value of said $\Delta P/P$ signal is below a predetermined value.

7. A fuel control as claimed in claim 6 wherein said other control parameter is W_f/P where W_f is fuel flow in pounds per hour.