United States Patent

Nelson et al.

[15] **3,636,335**

[45] **Jan. 18, 1972**

[54] TURBINE INLET TEMPERATURE COMPUTER

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[22] Filed: **Aug. 3, 1970**

[21] Appl. No.: **60,305**

[52] **U.S. Cl.**.....**235/193**, 235/151.34, 235/195

[51] **Int. Cl.**.....**G06g 7/16**, G06g 7/57

[58] **Field of Search**.....235/193, 194, 195, 196, 151.3, 235/151.34, 197; 207/229; 328/160, 161

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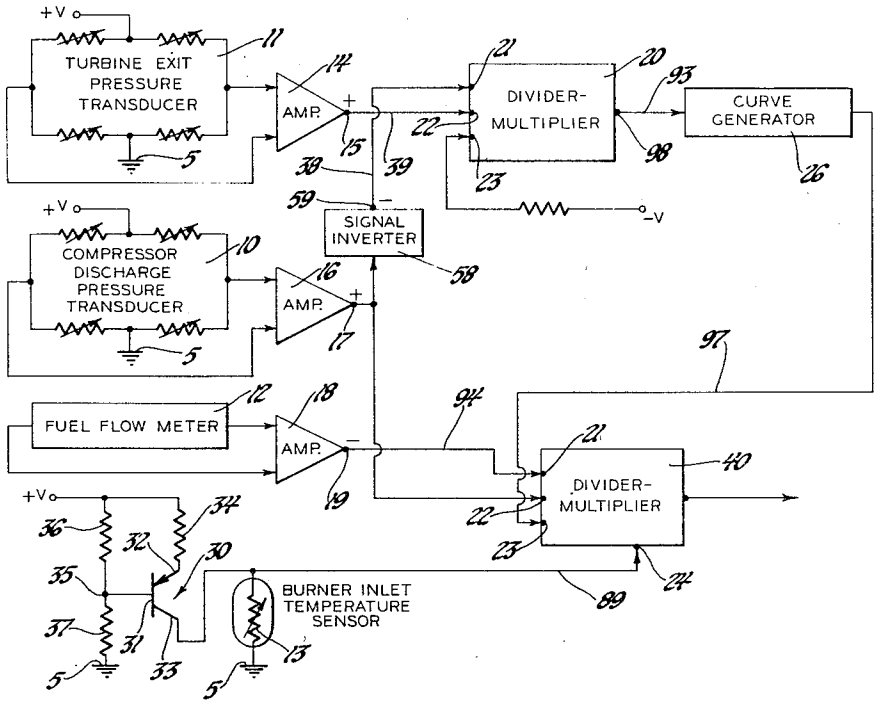
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[57] **ABSTRACT**

The turbine expansion ratio is calculated by a divider-multiplier circuit which divides a direct current compressor discharge pressure signal of a magnitude proportional to the compressor discharge pressure by a direct current turbine exit pressure signal of a magnitude proportional to the turbine exit pressure to produce a direct current turbine expansion ratio signal of a magnitude proportional to the turbine expansion ratio. A curve generator responsive to the turbine expansion ratio signal produces the reciprocal of a K factor signal which is a function of the turbine expansion ratio signal. A direct current mass fuel flow signal of a magnitude proportional to the mass fuel flow is divided by the compressor discharge pressure signal and the quotient multiplied by the reciprocal of the K factor signal in a second divider-multiplier circuit and a direct current burner inlet temperature signal of a magnitude proportional to the burner inlet temperature is added to this product to provide a direct current signal of a magnitude proportional to the computed turbine inlet temperature.

4 Claims, 7 Drawing Figures



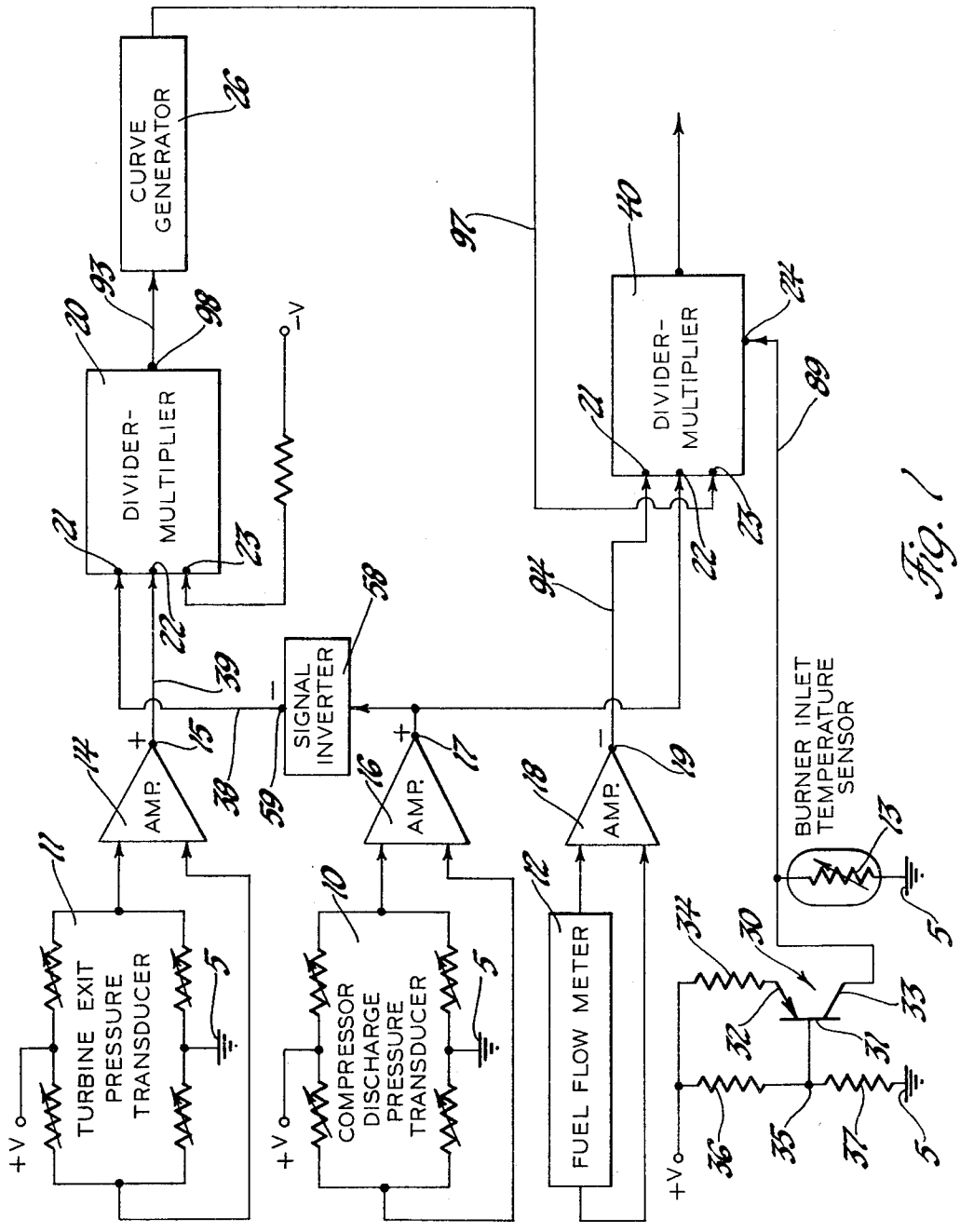


Fig. 1

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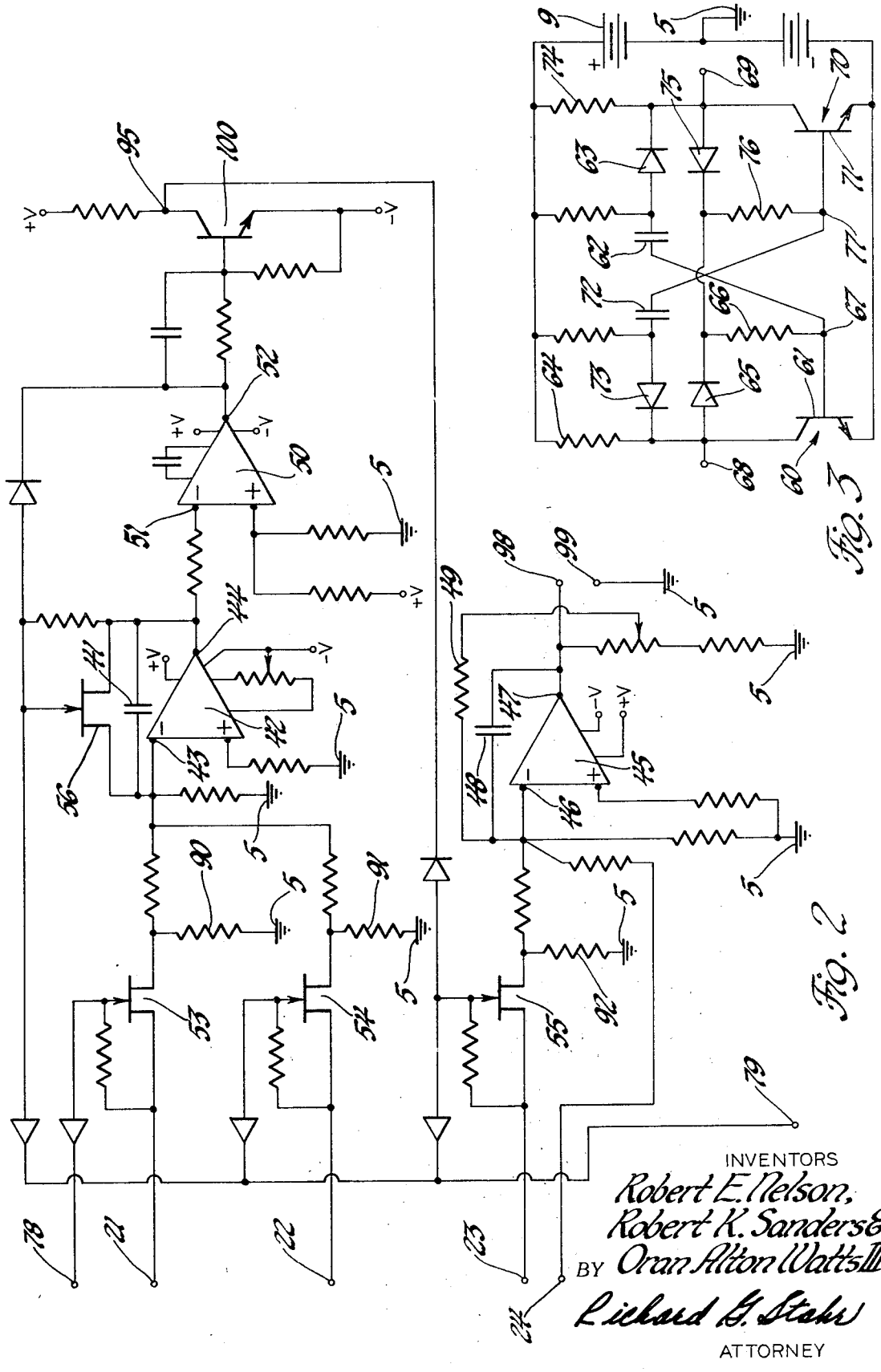


Fig. 2

Fig. 3

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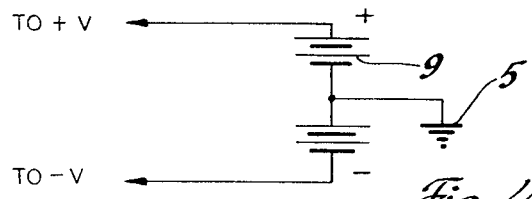


Fig. 4

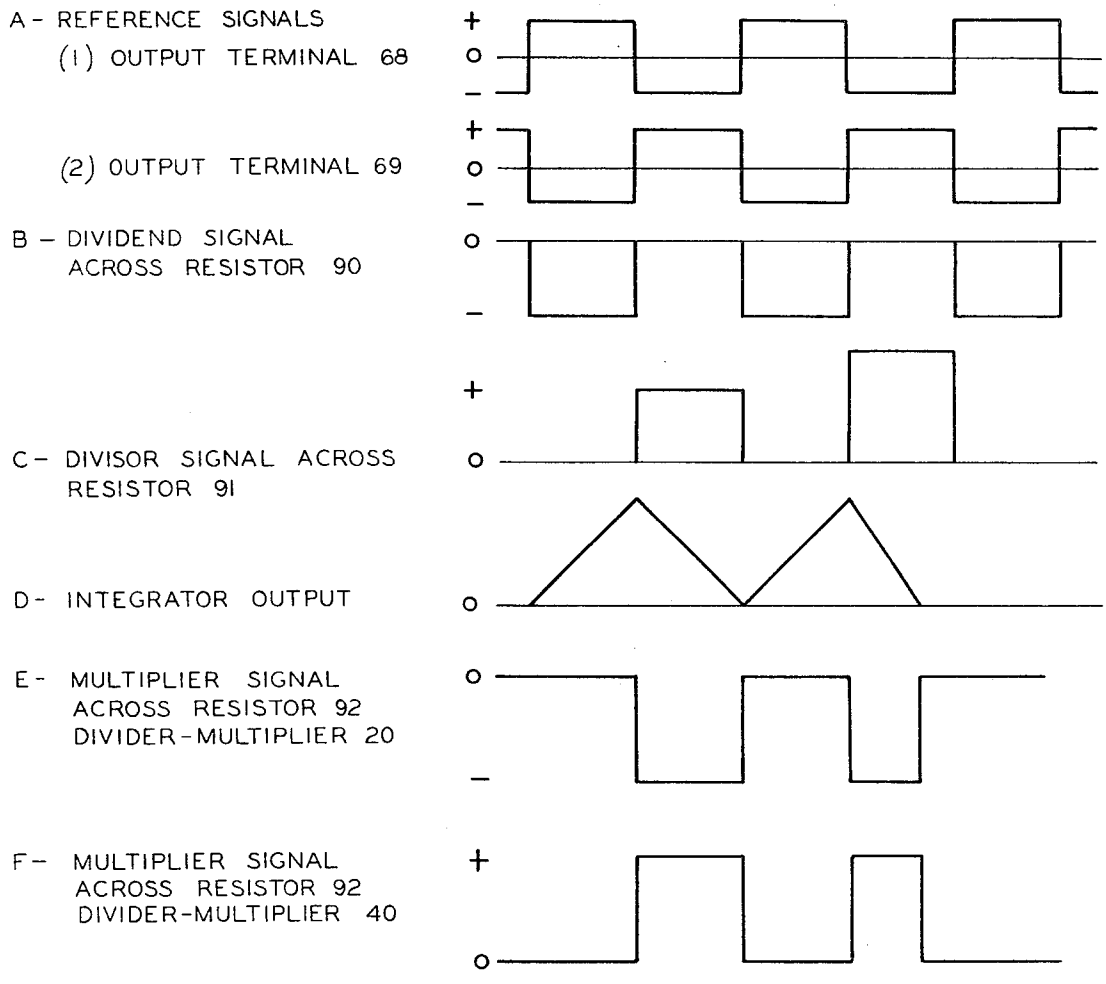


Fig. 6

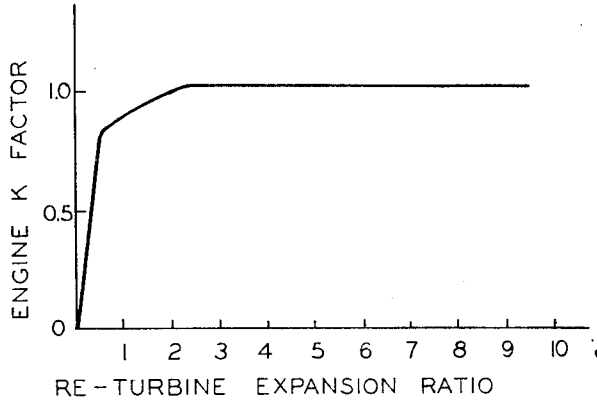


Fig. 5

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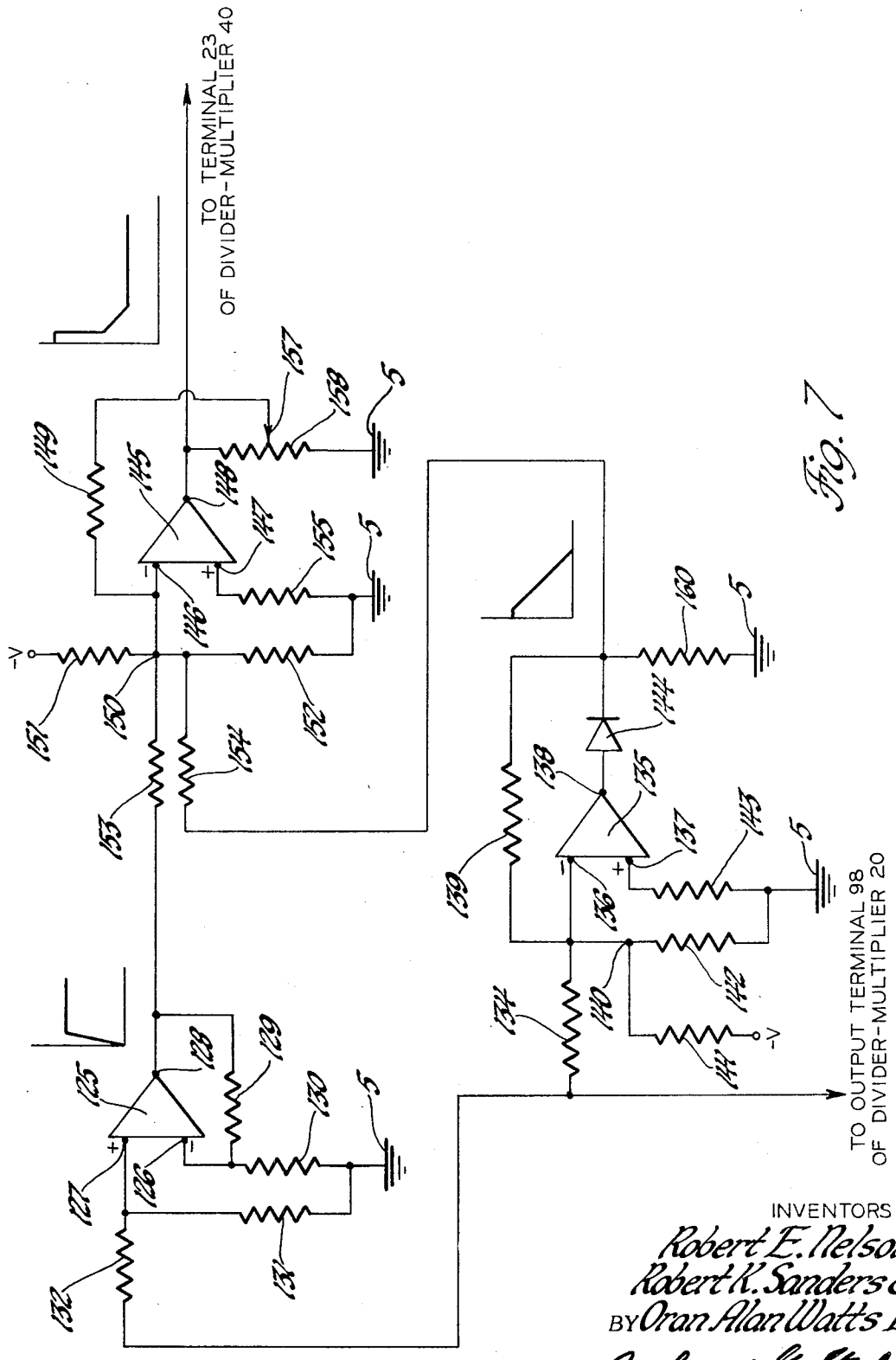


Fig. 7

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TURBINE INLET TEMPERATURE COMPUTER

The invention herein described was made in the course of work under contract or subcontract thereunder with the Department of Defense.

This invention is directed to a turbine inlet temperature computer and, more specifically, to a turbine inlet temperature computer which computes the turbine inlet temperature of a gas turbine-type engine on the basis of the compressor discharge pressure, the turbine exit pressure, the mass fuel flow and the burner inlet temperature.

Because of the extremely high turbine inlet temperatures proposed and being considered for further turbine type engines, the capability of thermocouple designs, even with the use of rare and noble metals, may be exceeded. Consequently, it is imperative that the turbine inlet temperature be synthesized from readily obtainable engine operating parameters which do not require thermocouples or other types of probes in the high temperature combustion gases of turbine-type engines.

It has been found that the inlet temperature of the turbine stage of a gas turbine type engine may be accurately calculated on the basis of compressor discharge pressure, turbine exit pressure, mass fuel flow and burner inlet temperature. Therefore, the turbine inlet temperature computer of this invention has been designed to solve the following equation:

$TIT = BIT + C(Wf/CDP) \times (1/K)$ where:

TIT = Turbine Inlet Temperature

BIT = Burner Inlet Temperature

CDP = Compressor Discharge Pressure

Wf = Mass Fuel Flow

C = Engine Constant

K = Engine Airflow Factor described below

This equation is valid provided no air is bled from the turbine after the compressor discharge pressure is measured or, in the event of an air bleed off, the amount is known.

The factor K in this equation is an expression of the flow of air through the turbine and may be determined for each turbine through tests. The value of the K factor is minimum at starting or low engine speeds and increases with engine speed until the value is unity while the turbine is operating in a choked condition.

It is, therefore, an object of this invention to provide an improved turbine inlet temperature computer.

It is another object of this invention to provide an improved turbine inlet temperature computer which eliminates the necessity of thermocouples or other types of probes in the high temperature combustion gases of turbine-type engines.

It is a further object of this invention to provide an improved turbine inlet temperature computer for computing the turbine inlet temperature of a gas turbine-type engine on the basis of readily obtainable engine operating parameters such as compressor discharge pressure, turbine exit pressure, mass fuel flow and burner inlet temperature.

In accordance with this invention, a turbine inlet temperature computer for computing the turbine inlet temperature of a gas turbine type engine on the basis of respective direct current electrical signals of a magnitude proportional to compressor discharge pressure, turbine exit pressure, mass fuel flow and burner inlet temperature is provided wherein the turbine expansion ratio is calculated by a divider-multiplier circuit in which the compressor discharge pressure electrical signal is divided by the turbine exit pressure electrical signal to produce a direct current signal which is the analog representation of the turbine expansion ratio, the mass fuel flow electrical signal is divided by the compressor discharge pressure electrical signal and the quotient is multiplied by the reciprocal of a K factor signal, which is a function of the turbine expansion ratio direct current signal, in another divider-multiplier circuit and the burner inlet temperature signal is added to this product to provide a computed turbine inlet temperature potential signal.

For a better understanding of the present invention, together with additional objects, advantages and features thereof, reference is made to the following description and accompanying drawings in which:

FIG. 1 is a block form diagram of the turbine inlet temperature computer of this invention;

FIG. 2 is a schematic diagram of a divider-multiplier circuit suitable for use with the turbine inlet temperature computer of this invention;

FIG. 3 is a schematic diagram of a reference signal source suitable for use with the divider-multiplier circuit of FIG. 2;

FIG. 4 illustrates a direct current operating potential source suitable for use with the turbine inlet temperature computer of this invention;

FIG. 5 is a curve showing a typical turbine expansion ratio vs. K factor relationship;

FIG. 6 is a set of curves useful in understanding the description of the divider-multiplier circuits used in the turbine inlet temperature computer of this invention; and

FIG. 7 is a schematic diagram, partially in block form, of a curve generator suitable for use with the turbine inlet temperature computer of this invention.

In FIGS. 1, 2, 3, 4 and 7 of the drawings, the point of reference or ground potential has been represented by the accepted schematic symbol and referenced by the numeral 5.

As has been hereinbefore brought out, the K factor of a turbine is an expression of airflow therethrough and may be determined by proper tests. The relationship between the K factor and turbine expansion ratio of a typical turbine is shown by the curve of FIG. 5. As the K factor is a function of the turbine expansion ratio, this term of the equation, hereinabove set forth, which is calculated by the turbine inlet temperature computer of this invention is obtained by calculating the turbine expansion ratio which is the compressor discharge pressure divided by the turbine exit pressure.

The direct current operating potential source is indicated in FIG. 4 to be a battery 9 having positive and negative polarity output terminals with respect to point of reference or ground potential 5. It is to be specifically understood, however, that any conventional direct current potential source having equal magnitude output potentials of a positive and a negative polarity with respect to point of reference or ground potential may be employed without departing from the spirit of the invention.

To reduce the complexity of FIGS. 1, 2, 3 and 7 of the drawings, the circuit connections to the direct current operating potential source 9 have not been shown. However, all points of the circuits of the FIGURES which are connected to the positive polarity output terminal of direct current operating potential source 9 are labeled +V and all points of the circuits of these FIGURES which are connected to the negative polarity output terminal of direct current operating potential source 9 are labeled −V.

Referring to FIG. 1 of the drawings, the turbine inlet temperature computer of this invention for computing the turbine inlet temperature of a gas turbine-type engine having at least a compressor stage, a burner stage and a turbine stage on the basis of the compressor discharge pressure, the turbine exit pressure, the mass fuel flow and the burner inlet temperature is set forth in block form and comprises a pressure transducer 10 for producing a compressor discharge pressure direct current potential signal of a magnitude proportional to the discharge pressure of the compressor stage; a pressure transducer 11 for producing a turbine exit pressure direct current potential signal of a magnitude proportional to the exit pressure of the turbine stage; circuitry responsive to the compressor discharge pressure signal and the turbine exit pressure signal for producing a turbine expansion ratio direct current potential output signal of a magnitude proportional to the expansion ratio of the turbine stage, may be a combined divider-multiplier circuit 20; circuitry responsive to the turbine expansion ratio signal for producing a direct current potential signal which is the reciprocal of the turbine K factor, may be a curve generator 26; circuitry for producing a mass fuel flow direct current potential signal of a magnitude proportional to the mass fuel flow to the turbine engine, may be a fuel flow meter 12, circuitry for producing a burner inlet temperature direct current potential signal of a magnitude proportional to the

inlet temperature of the burner stage, may be a temperature-sensitive variable resistor **13** and the associated circuitry; circuitry for dividing the mass fuel flow signal by the compressor discharge pressure signal; circuitry for multiplying the quotient of the mass fuel flow signal divided by the compressor discharge pressure signal by the reciprocal of the engine K factor potential signal and circuitry for adding the burner inlet temperature signal to the product of the quotient of the mass fuel flow signal divided by the compressor discharge pressure signal multiplied by the reciprocal of the engine K factor signal.

Without intention or inference of a limitation thereto, the divide and multiply circuits which calculate the turbine inlet temperature may be combined in a divider-multiplier circuit **40** of the type capable of dividing a dividend direct current potential signal by a divisor direct current potential signal and multiplying the quotient by a multiplier direct current potential signal having at least a respective input circuit for each the dividend, divisor, and multiplier electrical signals and a direct current potential signal summing input circuit for producing the turbine inlet temperature direct current potential output signal which is the quotient of the mass fuel flow signal divided by the compressor discharge pressure signal multiplied by the reciprocal of the engine K factor signal plus the burner inlet temperature signal.

To produce the direct current potential signal of a magnitude proportional to the discharge pressure of the compressor stage, hereinafter termed the compressor discharge pressure signal, and the direct current potential signal of a magnitude proportional to the exit pressure of the turbine stage, hereinafter termed the turbine exit pressure signal, pressure transducers of the type sensitive to static pressures for producing a direct current potential output signal proportional thereto may be employed for the compressor discharge pressure transducer **10** and the turbine exit pressure transducer **11**. Instruments of this type, suitable for use with the turbine inlet temperature computer of this invention, are commercially available from Servonic Instruments, Inc. of Willow Grove, Pa. and Costa Nasa, Calif. The important characteristics of these transducers is the ability to accurately sense static pressure. These transducers are located at the discharge of the compressor and the turbine, respectively, in a manner well known in the art and each is schematically illustrated in FIG. **1** as four variable resistors connected in a bridge configuration having one pair of diagonal junctions connected across the positive polarity output terminal of direct current operating potential source **9** and point of reference or ground potential **5**.

To produce a direct current potential signal of a magnitude proportional to the mass fuel flow to the turbine engine, hereinafter termed the weight of fuel flow signal, a real mass flow meter of the type which produces a direct current potential output signal of a magnitude proportional to the mass fuel flow may be employed in the line which supplies fuel to the turbine. Flow meters of this type are commercially available from the General Electric Company.

The turbine exit pressure signal, the compressor discharge pressure signal and the mass fuel flow signal may be amplified by respective amplifiers **14**, **16** and **18**, each having an output terminal **15**, **17** and **19**, respectively. As these amplifiers may be commercially available operational amplifiers or any other type direct current amplifier well known in the art and, per se, forms no part of this invention, each has been indicated in block form in FIG. **1**.

To produce a direct current potential signal of a magnitude proportional to the inlet temperature of the burner stage, hereinafter termed the burner inlet temperature signal, a platinum wire **13** may be located in the input of the burner stage in a manner well known in the art. This platinum wire may be energized by a constant direct current through a constant current circuit. A satisfactory constant current circuit may be in the form of a type PNP-transistor **30** having the usual base electrode **31**, emitter electrode **32** and collector electrode **33**. As is well known in the art, with a constant base-emitter bias potential applied to a transistor, the emitter-collector current flow therethrough remains substantially constant regardless of changes in supply potential. The emitter electrode **32** of transistor **30** is connected to the positive polarity output terminal of direct current operating potential source **9** through emitter resistor **34** and the collector electrode **33** is connected through the temperature sensitive resistor **13**, which may be a platinum wire, in series to point of reference or ground potential **5**. Consequently, the emitter-collector electrodes of type PNP-transistor **30** are properly poled for forward emitter-collector conduction therethrough. The base electrode **31** of transistor **30** is connected to junction **35** between series resistors **36** and **37** connected across the positive polarity terminal of direct current operating potential source **9** and point of reference or ground potential **5**. With this arrangement, a substantially constant direct current bias potential is applied across the emitter-base electrodes of type PNP-transistor **30** in the proper polarity relationship to produce emitter-base current flow through a type PNP-transistor. Consequently, a substantially constant emitter-collector current flows through type PNP-transistor **30**. As temperature sensitive resistor **13** is supplied from a constant current source, any change of current therethrough will be the result of a change in ambient temperature.

The circuitry responsive to the compressor discharge pressure signal and the turbine exit pressure signal for producing a turbine expansion ratio direct current potential output signal of a magnitude proportional to the expansion ratio of the turbine stage may be a divider-multiplier circuit **20** of a type identical to divider-multiplier circuit **40** wherein the compressor discharge pressure signal is divided by the turbine exit pressure signal.

Without intention or inference of a limitation thereto, one example of a divider-multiplier circuit suitable for use as divider-multiplier circuits **20** and **40** of the turbine inlet temperature computer of this invention is disclosed and described in detail in copending U.S. Pat. application, Ser. No. 57,202, filed July 22, 1970, and assigned to the same assignee as is this application and is set forth schematically in FIG. **2**.

Although the operation of the turbine inlet temperature computer of this invention will be described on the basis of the divider-multiplier circuit schematically set forth in FIG. **2**, it is to be specifically understood that alternate circuits may be used to perform the arithmetic operations performed by these circuits without departing from the spirit of the invention.

The divider-multiplier circuit of FIG. **2** is operated by an alternating current, square waveform reference signal source having two complementary polarity output circuits. One example of a square waveform alternating current reference signal source suitable for use with the divider-multiplier circuit of FIG. **2** is schematically set forth in FIG. **3**. This reference signal source may be a conventional astable or free-running multivibrator circuit including two type NPN-transistors **60** and **70** and the associated circuitry. Upon the application of the operating potential to this circuit, a forward base-emitter potential is applied across the base-emitter electrodes of both transistors **60** and **70** in the proper polarity relationship to produce base-emitter current flow through type NPN transistors. As the circuit parameters are not precisely equal, one of the other of transistors **60** or **70** will initially conduct through the collector-emitter electrodes thereof. For purposes of this specification, it will be assumed that transistor **60** initially conducts through the collector-emitter electrodes. Upon the conduction of transistor **60**, the base electrode **71** of transistor **70** is connected to the negative polarity output terminal of battery **9** through capacitor **72** and diode **73**, a condition which maintains transistor **70** not conductive, and capacitor **72** charges through a circuit which may be traced from the positive polarity output terminal of battery **9** through collector resistor **74**, diode **75**, resistor **76**, capacitor **72**, diode **73** and the collector-emitter electrodes of conducting transistor **60** to the negative polarity terminal of battery **9**. When capacitor **72**

has become charged, the potential upon junction 77 goes positive of a sufficient magnitude to produce base-emitter current flow through type NPN-transistor 70 to initiate collector-emitter current flow therethrough. Upon the conduction of transistor 70, the base electrode 61 of transistor 60 is connected to the negative polarity output terminal of battery 9 through capacitor 62 and diode 63, a condition which extinguishes transistor 60 and capacitor 62 charges through a circuit which may be traced from the positive polarity output terminal of battery 9, through collector resistor 64, diode 65, resistor 66, capacitor 62, diode 63 and the collector-emitter electrodes of conducting transistor 70 to the negative polarity terminal of battery 9. When capacitor 62 has become charged, the potential upon junction 67 goes positive of a sufficient magnitude to produce base-emitter current flow through type NPN-transistor 60 to initiate collector-emitter current flow therethrough. Upon the conduction of transistor 60, the base electrode 71 of transistor 70 is again connected to the negative polarity output terminal of battery 9 through the circuit previously described, consequently, transistor 70 extinguishes and capacitor 72 again begins to charge through the circuit previously described. This action continues with transistors 60 and 70 alternately conducting at a frequency determined by the values of resistors 74 and 76 and capacitor 72 and resistors 64 and 66 and capacitor 62. The output signals may be taken from the collector of respective transistors 60 and 70 through respective output terminals 68 and 69. While transistor 70 is conducting, a positive polarity output signal, with respect to point of reference or ground potential 5, is present upon output circuit terminal 68 and a negative polarity output signal, with respect to point of reference or ground potential 5, is present upon output circuit terminal 69. While transistor 60 is conducting, a negative polarity output signal, with respect to point of reference or ground potential 5, is present upon output circuit terminal 68 and a positive polarity output signal, with respect to point of reference or ground potential 5, is present upon output circuit terminal 69. These signals are graphically illustrated as curve A of FIG. 6. Consequently, this circuit provides a square waveform alternating current reference signal source having two complementary polarity output circuits. In a practical application of the circuit of this invention, the square waveform alternating current reference signal source had a frequency of 2 kilocycles.

The divider-multiplier circuits 20 and 40 of FIG. 1 are set forth schematically in FIG. 2 and have at least a respective input circuit for each the dividend, divisor and multiplier input signals which may be respective terminals 21, 22, and 23 and a summing input circuit which may be a terminal 24. It is to be specifically understood that terminals 21 through 24 may be any electrical device suitable for connection to external circuitry. Each divider-multiplier circuit also includes an operational amplifier 42 having an inverting input terminal 43, an output terminal 44 and a feedback capacitor 41, an operational amplifier 45 having an inverting input terminal 46, an output terminal 47 and a feedback capacitor 48 and resistor 49 and an operational amplifier 50 having an inverting input terminal 51 and an output terminal 52.

Operational amplifiers are high gain, direct current amplifiers, which are well known in the art and are commercially available, having an inverting input circuit, a noninverting input circuit and an output circuit. An input signal applied to the inverting input circuit of an operational amplifier produces an output signal of the opposite polarity and an input signal applied to the noninverting input circuit produces an output signal of the same polarity.

As is well known in the art, operational amplifiers may be converted to direct current signal integrating circuits by providing a feedback capacitor between the output circuit and the inverting input circuit. Consequently, operational amplifier 42 functions as a direct current signal integrating circuit.

Operational amplifier 45 operates as a direct current signal averaging circuit which produces an output signal of a magnitude proportional to the magnitudes of a series of direct current pulses applied to the inverting input circuit 46.

Operational amplifier 50, to the inverting input terminal 51 of which output terminal 44 of integrating operational amplifier 42 is connected, is operated in the open loop mode and functions as a sensitive direct current switch. Operational amplifier 50 produces an output signal of a negative polarity when the output signal of integrating operational amplifier 42 is of a positive polarity and an output signal of a positive polarity when the output signal of integrating operational amplifier 42 is of a negative polarity.

The source-drain electrodes of respective field effect transistors 53 and 54 are connected between input terminals 21 and 22 and the inverting input terminal 43 of integrating operational amplifier 42 and the source-drain electrodes of field effect transistor 55 are connected between input terminal 23 and inverting input terminal 46 of averaging operational amplifier 45. Each of these field effect transistors is of the N-channel type which is normally conductive through the source-drain electrodes unless maintained not conductive by a negative polarity signal upon the gate electrode thereof. Field effect transistors 53, 54 and 55 function as potential sensitive switches to apply the input signals to the divider-multiplier circuit in the proper sequence. Consequently, output terminal 68 of the source of reference signals of FIG. 3 is connected to the gate electrode of field effect transistor 53 through input terminal 78 through a lead (not shown) interconnecting these two terminals and output terminal 69 of the reference signal source of FIG. 3 is connected to the gate electrode of each of field effect transistors 54 and 55 through input terminal 79 through a lead (not shown) interconnecting these two terminals.

For purposes of this specification, and without intention or inference of a limitation thereto, it will be assumed that the amplified compressor discharge pressure signal, the amplified turbine exit pressure signal and the burner inlet temperature signal are of a positive polarity and the amplified mass fuel flow signal is of a negative polarity.

The positive polarity compressor discharge pressure signal is applied through amplifier 16 and a signal inverter 58 to the dividend input terminal 21 of divider-amplifier 20 through a lead 38 connecting output terminal 59 of signal inverter 58 to dividend input terminal 21 of divider-multiplier 20.

The positive polarity turbine exit pressure signal is applied through amplifier 14 to the divisor input terminal 22 of divider-multiplier 20 through a lead 39 connecting output terminal 15 of amplifier 14 to divisor input terminal 22 of divider-multiplier 20.

Input terminal 24 of divider-multiplier 20 is not utilized in divider-multiplier 20.

As signal inverter 58 may be any conventional inverter circuit well known in the art and forms no part of this invention, it has been indicated in block form in FIG. 1.

Divider-multiplier circuit 20 calculates the turbine expansion ratio by dividing the compressor discharge pressure signal by the turbine exit pressure signal. As this divider-multiplier circuit requires a multiplier input signal to produce an output, the quotient of the compressor discharge pressure signal and the turbine exit pressure signal is multiplied by a preselected constant direct current potential signal which may be obtained from the negative polarity output terminal of direct current operating potential source 9.

Over those half cycles of the alternating current reference signals during which output terminals 68 and 69 of the reference signal source of FIG. 3 are of a positive and a negative polarity, respectively, with respect to point of reference or ground potential 5, the positive polarity signal upon output terminal 68, applied to the gate electrode of field effect transistor 53, permits this device to conduct, and the negative polarity signal upon output terminal 69, applied to the gate electrodes of field effect transistors 54, 55 and 56, holds these devices not conductive. While field effect transistor 53 conducts, the inverted compressor discharge pressure signal appears across load resistor 90, curve B of FIG. 6. The negative polarity inverted compressor discharge pressure signal, therefore, is applied to the inverting input circuit terminal 43 of in-

tegrating operational amplifier 42 which integrates this negative polarity dividend signal in a positive direction for the duration of these half cycles of the reference signals, as shown in curve D of FIG. 6. As the output signal upon output circuit terminal 44 of integrating operational amplifier 42 is of a positive polarity, the output signal upon output circuit terminal 52 of operational amplifier 50 is of a negative polarity. With a negative polarity signal present upon the output circuit 52 of operational amplifier 50, type NPN-transistor 100 is not conductive. Consequently, the potential upon junction 95 is of a positive polarity. This signal is of no effect at this time as the negative polarity reference signal maintains field effect transistor 55 not conductive.

Over the alternate half cycles of the alternating current reference signals during which output terminals 68 and 69 of the reference signal source of FIG. 3 are of a negative and a positive polarity, respectively, with respect to point of reference or ground potential 5, the negative polarity output signal upon output terminal 68 extinguishes field effect transistor 53 to remove the compressor discharge pressure signal from integrating operational amplifier 42 and the positive polarity signal upon output terminal 69 permits field effect transistors 54 and 55 to conduct. Although this signal is also applied to the gate electrode of reset field effect transistor 56, this device is maintained not conductive by the negative polarity signal present upon output circuit terminal 52 of operational amplifier 50 which is applied to the gate electrode thereof. While field effect transistors 54 and 55 conduct, the positive polarity turbine exit pressure signal appears across load resistor 91, curve C of FIG. 6 and, simultaneously, the constant negative polarity multiplier signal appears across load resistor 92, curve E of FIG. 6. The positive polarity turbine exit pressure signal, therefore, is applied to the inverting input circuit terminal 43 of integrating operational amplifier 42 which integrates this positive polarity divisor signal in a negative polarity direction, as shown in curve D of FIG. 6.

When integrating operational amplifier 42 has integrated the turbine exit pressure signal to substantially zero, operational amplifier 50 switches to its alternate state in which the output signal is of a positive polarity. This positive polarity signal produces base-emitter current flow through type NPN-transistor 100 to initiate collector-emitter current flow therethrough. Upon the conduction of transistor 100 through the collector-emitter electrodes, the potential upon junction 95 goes negative and is applied to the gate electrode of field effect transistor 55 to extinguish field effect transistor 55 which disconnects the constant multiplier signal from the averaging circuit. Simultaneously, the positive polarity signal upon output circuit terminal 52 of operational amplifier 50 permits source-drain current flow through reset field effect transistor 56, a condition which resets the output signal upon output circuit terminal 44 of integrating operational amplifier 42 to zero.

The magnitude of the dividend signal determines the magnitude of the integrated dividend signal and the magnitude of the divisor signal determines the length of time required for integrating operational amplifier 42 to integrate the divisor signal in the opposite direction to substantially zero. Consequently, the length of time required for integrating operational amplifier 42 to integrate the divisor signal to substantially zero is a function of the ratio of the relative magnitudes of the divisor signal and the dividend signal and is an analog representation of the quotient of the dividend signal divided by the divisor signal. For example, as the dividend signal is integrated in a first direction by integrating operational amplifier 42 for the duration of a complete half cycle of the reference signals, the length of time required for integrating operational amplifier 42 to integrate a divisor signal of a magnitude precisely equal to the magnitude of the dividend signal to substantially zero is equal to the period of a complete half cycle of the reference signals, or unity, and to integrate a divisor signal of a magnitude precisely equal to twice the magnitude of the dividend signal to substantially zero is equal to the period of one-fourth cycle of the reference signals, or 0.5. As the multiplier signal appears across load resistor 92 for the period of time required for integrating operational amplifier 42 to integrate the divisor signal to substantially zero, the width of the multiplier signal pulse across load resistor 92 is also an analog representation of the quotient of the dividend signal divided by the divisor signal. Consequently, the multiplier signal appears across load resistor 92 as a series of direct current pulses of a magnitude equal to the magnitude of the multiplier signal and for a duration of time which is the analog representation of the quotient of the dividend signal divided by the divisor signal. These direct current pulses are averaged by operational amplifier 45 and appear as a direct current potential signal across output terminals 98 and 99 which represents, in analog form, the product of the multiplier signal and the quotient of the dividend signal divided by the divisor signal. The output signal of averaging operational amplifier 45, therefore, is a direct current potential signal of a magnitude proportional to the turbine expansion ration.

The curve of FIG. 5 illustrates the relationship between the turbine expansion ratio and the K factor of a typical turbine engine which may be determined by test. Consequently, the turbine expansion ratio-K relationship for any given engine may be determined and a curve generator may be designed which will produce an electrical signal corresponding to the reciprocal of the K factor in response to the turbine expansion ratio signal present upon the output circuit terminal 98 of divider-multiplier 20. The output signal from divider-multiplier 20 is applied to the input circuit of curve generator 26 through lead 93 which connects output terminal 98 of divider-multiplier 20 to the input circuit of curve generator 26. Curve generator 26 may be any one of the many curve generators well known in the art of the type which provides an output signal which is a nonlinear function of an input signal. One example of a curve generator which may be used with the computer circuit of this invention is set forth partially in schematic and partially in block form in FIG. 7.

The curve generator of FIG. 7 includes three operational amplifiers 125, 135 and 145. The inverting input circuit terminal 126 and the noninverting input circuit terminal 127 of operational amplifier 125 are connected to point of reference or ground potential 5 through respective resistors 130 and 131 and output circuit terminal 128 is connected to the inverting input circuit terminal 126 through feedback resistor 129. Consequently, in the absence of an input signal, the output of operational amplifier 125 is zero, as shown by the curve adjacent the output thereof. The inverting input circuit terminal 136 of operational amplifier 135 is connected to junction 140 between series resistors 141 and 142 which are connected across the negative polarity output terminal of direct current operating potential source 9 and point of reference or ground potential 5, the non-inverting input circuit terminal 137 is connected to point of reference or ground potential 5 through resistor 143 and the output circuit terminal is connected to the inverting input circuit terminal 136 through a diode 144 and a feedback resistor 139. Consequently, in the absence of an input signal, the output of operational amplifier 135 is of a positive polarity and of a magnitude determined by the potential drop across resistor 142, as is shown by the curve adjacent the output circuit thereof. The inverting input circuit terminal 146 of operational amplifier 145 is connected to junction 150 between series resistors 151 and 152 connected across the negative polarity output terminal of direct current operating potential source 9 and point of reference or ground potential 5, the noninverting input circuit terminal 147 is connected to point of reference or ground potential 5 through resistor 155 and the output circuit terminal 148 is connected to the inverting input circuit terminal 146 through the movable contact 157 of potentiometer 158 and feedback resistor 149. Consequently, in the absence of an input signal, the output of operational amplifier 145 is of a positive polarity and of a magnitude determined by the potential drop across resistor 151, as is shown by the curve adjacent the output circuit

thereof. The positive polarity turbine expansion ratio signal is applied to the noninverting input circuit terminal 127 of operational amplifier 125 through input resistor 132 and to the inverting input circuit terminal 136 of operational amplifier 135 through input resistor 134. Resistors 129 and 132 are proportioned to provide a high gain for operational amplifier 125 and resistors 139 and 134 are proportioned to provide a gain for operational amplifier 135 of a degree less than the gain of operational amplifier 125. Therefore, as the positive polarity turbine expansion ratio signal increases in magnitude with an increase of turbine speed, the output of operational amplifier rises steeply in a positive polarity direction until operational amplifier 125 saturates, after which the output signal remains substantially constant, as is shown in the curve adjacent the output thereof, and the output signal of operational amplifier 135 decreases in a negative polarity direction at a rate slower than the increase of the output of operational amplifier 125 until the output reaches zero, as shown by the curve adjacent the output thereof. Diode 144, which becomes reverse biased when the output circuit terminal 138 of operational amplifier 135 goes negative, prevents the output signal appearing across load resistor 160 from going below zero or negative. As the output signal of operational amplifier 125 is applied to the inverting input circuit terminal 146 of operational amplifier 145 through input resistor 153 and the output of operational amplifier 135 is also applied to the inverting input circuit terminal 146 of operational amplifier 145 through input resistor 154, the rapidly increasing output of operational amplifier 125 in a positive polarity direction results in an output signal from operational amplifier 145 which rapidly decreases in a negative polarity direction, as shown in the curve adjacent the output thereof, until operational amplifier 125 substantially saturates. At this time, the negative going output potential from operational amplifier 135 becomes the dominant factor influencing the output signal from operational amplifier 145. As this signal is decreasing in a negative direction, the output of operational amplifier 145 decreases in a negative direction at a much slower rate to provide the knee of the curve of the output signal of operational amplifier 145. When the output signal from operational amplifier 135 has reached zero, the input signal to operational amplifier 145 no longer changes and the output signal therefrom remains substantially constant. Consequently, the output signal from curve generator 26 closely approximates the reciprocal of the engine turbine expansion ratio-K factor curve shown in FIG. 5. The level of the constant portion of this curve is determined by adjusting movable contact 157 of potentiometer 158, an operation which operates to provide a signal for the constant C term of the equation hereinabove set forth. For any given engine for which the turbine expansion ratio-K factor relationship is known, resistors 129 and 132 of operational amplifier 125, resistors 139, 134 and 141 of operational amplifier 135 and resistors 149, 153, 154 and 151 of operational amplifier 145 may be proportioned to provide an output signal which closely approximates the reciprocal of the turbine expansion ratio-K factor curve of the engine.

The negative polarity weight of fuel flow signal is applied through amplifier 18 to the dividend input terminal 21 of divider-multiplier circuit 40 through lead 94 connecting output terminal 19 of amplifier 18 to the dividend input terminal 21 of divider-multiplier 40.

The positive polarity compressor discharge pressure signal is applied through amplifier 16 to the divisor input terminal 22 of divider-multiplier 40 through a lead 96 connecting output terminal 17 of amplifier 16 to the divisor input terminal 22 of divider-multiplier 40.

The reciprocal of the turbine expansion ratio signal produced by curve generator 26 is applied to the multiplier input terminal 23 of divider-multiplier 40 through a lead 97 connecting the output of curve generator 26 to multiplier input terminal 23 of divider-multiplier 40.

The positive polarity burner inlet temperature signal appearing across variable resistor 13 is applied to the summing input terminal 24 of divider-multiplier 40 through lead 89.

Simultaneously with the calculation of the turbine expansion ratio by multiplier-divider 20, over those half cycles of the alternating current reference signals during which output terminals 68 and 69 of the reference signal source of FIG. 3 are of a positive and a negative polarity, respectively, with respect to point of reference or ground potential 5, the positive polarity signal upon output terminal 68, applied to the gate electrode of field effect transistor 53, permits this device to conduct, and the negative polarity signal upon output terminal 69, applied to the gate electrodes of respective field effect transistors 54, 55 and 56, holds these devices not conductive. While field effect transistor 53 conducts, the weight of fuel flow signal appears across load resistor 90, curve B of FIG. 6. The negative polarity weight of fuel flow signal, therefore, is applied to the inverting input circuit terminal 43 of integrating operational amplifier 42 which integrates this negative polarity dividend signal in a positive direction for the duration of these half cycles of the reference signals, as shown in curve D of FIG. 6. As the output signal upon output circuit terminal 44 of integrating operational amplifier 42 is of a positive polarity, the output signal upon output circuit terminal 52 of operational amplifier 50 is of a negative polarity. With a negative polarity signal present upon the output circuit of operational amplifier 50, type NPN-transistor 100 is not conductive. Consequently, the potential upon junction 95 is of a positive polarity. This signal is of no effect at this time as the negative polarity reference signal maintains field effect transistor 55 not conductive.

Over the alternate half cycles of the alternating current reference signals during which output terminals 68 and 69 of the reference signal source of FIG. 3 are of a negative and a positive polarity, respectively, with respect to point of reference or ground potential 5, the negative polarity output signal upon output terminal 68 extinguishes field effect transistor 53 to remove the weight of fuel flow signal from integrating operational amplifier 42 and the positive polarity signal upon output terminal 69 permits field effect transistors 54 and 55 to conduct. Although this signal is also applied to the gate electrode of reset field effect transistor 56, this device is maintained not conductive by the negative polarity signal present upon output circuit terminal 52 of operational amplifier 50 which is applied to the gate electrodes thereof. While field effect transistors 54 and 55 conduct, the positive polarity compressor discharge pressure signal appears across load resistor 91, curve C of FIG. 6, and simultaneously, the positive polarity reciprocal of the turbine expansion ratio signal appears across load resistor 92, curve F of FIG. 6. The positive polarity compressor discharge pressure signal, therefore, is applied to the inverting circuit terminal 43 of integrating operational amplifier 42 which integrates this positive polarity divisor signal in a negative polarity direction, as shown in curve D of FIG. 6.

When integrating operational amplifier 42 has integrated the compressor discharge pressure signal to substantially zero, operational amplifier 50 switches to its alternate state in which the output signal is of a positive polarity. This positive polarity signal produces base-emitter current flow through type NPN-transistor 100 to initiate collector-emitter current flow therethrough. Upon the conduction of transistor 100 through the collector-emitter electrodes, the potential upon junction 95 goes negative and is applied to the gate electrode of field effect transistor 55 which disconnects the reciprocal of the turbine expansion ratio signal from the averaging circuit. Simultaneously, the positive polarity signal upon output circuit terminal 52 of operational amplifier 50 permits source-drain current flow through reset field effect transistor 56, a condition which resets the output signal upon output circuit terminal 44 of integrating operational amplifier 42 to zero.

As the positive polarity burner inlet temperature signal is applied to inverting input circuit terminal 46 of averaging

operational amplifier 45 this signal is summed with or added to the product of the quotient of the weight of fuel flow signal divided by the compressor discharge signal multiplied by the reciprocal of the turbine expansion ratio signal. Consequently, the output signal appearing across output terminals 98 and 99 of divider-multiplier 40 is a direct current potential signal of a negative polarity and of a magnitude which is the analog representation of the turbine inlet temperature which has been computed by the turbine inlet temperature computer of this invention which calculated the equation hereinabove set forth.

Although the foregoing description was on the basis of specific electrical devices and electrical polarities, it is to be specifically understood that alternate electrical devices and compatible electrical polarities which produce the same results may be substituted therefor without departing from the spirit of the invention.

While a preferred embodiment of the present invention has been shown and described, it will be obvious to those skilled in the art that various modifications and substitutions may be made without departing from the spirit of the invention which is to be limited only within the scope of the appended claims.

What is claimed is:

1. A turbine inlet temperature computer for computing the turbine inlet temperature of a gas turbine-type engine having at least a compressor stage, a burner stage and a turbine stage on the basis of the compressor discharge pressure, the turbine exit pressure, the mass fuel flow and the burner inlet temperature comprising: means for producing a compressor discharge pressure direct current potential signal of a magnitude proportional to the discharge pressure of said compressor stage, means for producing a turbine exit pressure direct current potential signal of a magnitude proportional to the exit pressure of said turbine stage, means responsive to said compressor discharge pressure signal and said turbine exit pressure signal for producing a turbine expansion ratio direct current potential output signal of a magnitude proportional to the expansion ratio of said turbine stage, means responsive to said turbine expansion ratio signal for producing a direct current potential signal which is the reciprocal of said turbine K factor, means for producing a mass fuel flow direct current potential signal of a magnitude proportional to the mass fuel flow to said turbine engine, means for producing a burner inlet temperature direct current potential signal of a magnitude proportional to the inlet temperature of said burner stage, means for dividing said mass fuel flow signal by said compressor discharge pressure signal, means for multiplying the quotient of said mass fuel flow signal divided by said compressor discharge pressure signal by said reciprocal of said turbine K factor signal, and means for adding said burner inlet temperature signal to the product of the quotient of said mass fuel flow signal divided by said compressor discharge pressure signal multiplied by said reciprocal of said turbine K factor signal.

2. A turbine inlet temperature computer for computing the turbine inlet temperature of a gas turbine-type engine having at least a compressor stage, a burner stage and a turbine stage on the basis of the compressor discharge pressure, the turbine exit pressure, the mass fuel flow and the burner inlet temperature comprising: means for producing a compressor discharge pressure direct current potential signal of a magnitude proportional to the discharge pressure of said compressor stage, means for producing a turbine exit pressure direct current potential signal of a magnitude proportional to the exit pressure of said turbine stage, means for dividing said compressor discharge pressure signal by said turbine exit pressure signal for producing a turbine expansion ratio direct current potential output signal of a magnitude proportional to the expansion ratio of said turbine stage, means responsive to said turbine expansion ratio signal for producing a direct current potential signal which is the reciprocal of said turbine K factor, means for producing a mass fuel flow direct current potential signal of a magnitude proportional to the mass fuel flow to said turbine engine, means for producing a burner inlet temperature direct current potential signal of a magnitude proportional to the inlet temperature of said burner stage, means for dividing said mass fuel flow signal by said compressor discharge pressure signal, means for multiplying the quotient of said mass fuel flow signal divided by said compressor discharge pressure signal by said reciprocal of said turbine K factor signal, and means for adding said burner inlet temperature signal to the product of the quotient of said mass fuel flow signal divided by said compressor discharge pressure signal multiplied by said reciprocal of said turbine K factor signal.

3. A turbine inlet temperature computer for computing the turbine inlet temperature of a gas turbine-type engine having at least a compressor stage, a burner state and a turbine stage on the basis of the compressor discharge pressure, the turbine exit pressure, the mass fuel flow and the burner inlet temperature comprising: means for producing a compressor discharge pressure direct current potential signal of a magnitude proportional to the discharge pressure of said compressor stage, means for producing a turbine exit pressure direct current potential signal of a magnitude proportional to the exit pressure of said turbine stage, means responsive to said compressor discharge pressure signal and said turbine exit pressure signal for producing a turbine expansion ratio direct current potential output signal of a magnitude proportional to the expansion ratio of said turbine stage, means responsive to said turbine stage, means responsive to said turbine expansion ratio signal for producing a direct current potential signal which is the reciprocal of said turbine K factor, means for producing a mass fuel flow direct current potential signal of a magnitude proportional to the mass fuel flow to said turbine engine, means for producing a burner inlet temperature direct current potential signal of a magnitude proportional to the inlet temperature of said burner stage, a divider-multiplier circuit of the type capable of dividing the dividend direct current potential signal by a divisor direct current potential signal and multiplying the quotient by a multiplier direct current potential signal having at least a respective input circuit for each the dividend, divisor and multiplier electric signals and a direct current potential summing input circuit for producing the turbine inlet temperature direct current potential output signal which is the quotient of said mass fuel flow signal divided by said compressor discharge pressure signal multiplied by said reciprocal of said turbine K factor signal plus said burner inlet temperature signal, means for applying said mass fuel flow signal to said dividend input circuit of said second divider-multiplier circuit, means for applying said compressor discharge pressure signal to said divisor input circuit of said second divider-multiplier circuit, means for applying said reciprocal of said turbine K factor signal to said multiplier input circuit of said second divider-multiplier circuit, and means for applying said burner inlet temperature signal to said summing input circuit of said second divider-multiplier circuit.

4. A turbine inlet temperature computer for computing the turbine inlet temperature of a gas turbine-type engine having at least a compressor stage, a burner stage and a turbine stage on the basis of the compressor discharge pressure, the turbine exit pressure, the mass fuel flow and the burner inlet temperature comprising: means for producing a compressor discharge pressure direct current potential signal of a magnitude proportional to the discharge pressure of said compressor stage, means for producing a turbine exit pressure direct current potential signal of a magnitude proportional to the exit pressure of said turbine stage, means for producing a constant direct current potential signal of a selected magnitude, a first divider-multiplier circuit of the type capable of dividing a dividend direct current potential signal by a divisor direct current potential signal and multiplying the quotient by a multiplier direct current potential signal having at least a respective input circuit for each the dividend, divisor and multiplier input signals for producing a turbine expansion ratio direct current potential output signal of a magnitude proportional to the expansion ratio of said turbine stage, means for applying

said compressor discharge pressure signal to said dividend input circuit of said first divider-multiplier circuit, means for applying said turbine exit pressure signal to said divisor input circuit of said first divider-multiplier circuit, means for applying said constant direct current potential signal to said multiplier input circuit of said first divider-multiplier circuit, a curve generator responsive to said turbine expansion ratio signal for producing a direct current potential output signal which is the reciprocal of the turbine K factor, means for applying said turbine expansion ratio output signal from said first divider-multiplier circuit to said curve generator, means for producing a mass fuel flow direct current potential signal of a magnitude proportional to the weight of fuel flow to said turbine engine, means for producing a burner inlet temperature direct current potential signal of a magnitude proportional to the inlet temperature of said burner stage, a second divider-multiplier circuit of the type capable of dividing a dividend direct current potential signal by a divisor direct current potential signal and multiplying the quotient by a multiplier direct current potential signal having at least a respective input circuit for each the dividend, divisor and multiplier input signals and a direct current potential signal summing input circuit for producing the turbine inlet temperature direct current potential output signal which is the quotient of said mass fuel flow signal divided by said compressor discharge pressure signal multiplied by the reciprocal of said turbine K factor signal plus said burner inlet temperature signal, means for applying said mass fuel flow signal to said dividend input circuit of said second divider-multiplier circuit, means for applying said compressor discharge pressure signal to said divisor input circuit of said second divider-multiplier circuit, means for applying said curve generator output signal to said multiplier input circuit of said second divider-multiplier circuit, and means for applying said burner inlet temperature signal to said summing input circuit of said second divider-multiplier circuit.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,636,335 Dated January 18, 1972

Inventor(s) Robert E. Nelson, Robert K. Sanders, Oran Alton Watts

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 1, line 11, "further" should read -- future --. Column 6, line 39, "divider-amplifier" should read -- divider-multiplier --. Column 8, line 56, after "terminal" insert -- 138 --. Column 10, line 52, after "inverting" insert -- input --. Column 12, lines 25 and 26, delete "means responsive to said turbine stage,"; line 34, after "dividing" delete "the" and insert -- a --; line 39, after "potential" insert -- signal --.

Signed and sealed this 6th day of June 1972.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents