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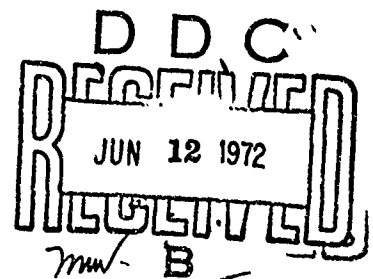
**AUTOMATIC THROTTLE CONTROL
FOR TRANSPORT AIRCRAFT
WITH MAXIMUM QUADRANT POSITION
LIMITED BY ENGINE PRESSURE RATIO**

β
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THE BENDIX CORPORATION

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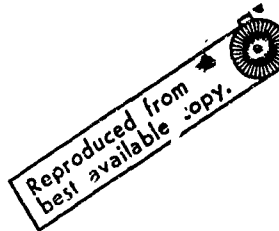
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FOR TRANSPORT AIRCRAFT
WITH MAXIMUM QUADRANT POSITION
LIMITED BY ENGINE PRESSURE RATIO

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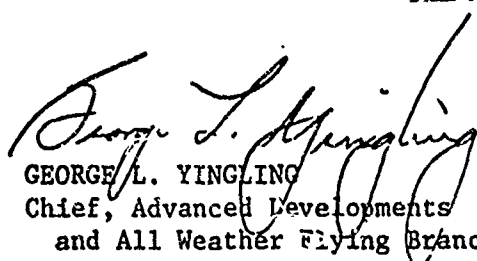
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FOREWORD

This report was prepared jointly by the Navigation and Control Division of The Bendix Corporation under USAF Contract No. AF33(615) 69-C-1468 and the Air Force Flight Dynamics Laboratory. The work was conducted under the cognizance of the Advanced Developments and All Weather Flying Branch, Flight Control Division, Air Force Flight Dynamics Laboratory, with Mr. R. V. Wible serving as task engineer.

Circuit designs and synthesis were conducted by personnel of Department 7211, Flight Systems Laboratory, of The Bendix Corporation, Navigation and Control Division. Personnel of DOAC-ST served as project pilots and provided design commentary on engine limitations and performance characteristics. The contributions of all personnel assigned to the Speckled Trout aircraft are sincerely appreciated.

This technical report has been reviewed and is approved.


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ABSTRACT

This report describes an automatic throttle control system that limits maximum throttle lever position as a function of Engine Pressure Ratio. Limit EPR is sensed by an outside air temperature gauge calibrated in EPR as based on thrust level limits contained in the aircraft operator's manual. Limit control of EPR is accomplished by stopping the throttle lever when the sensed EPR, as read on the standard engine instruments (rescaled for use in the throttle system) equals the temperature sensed limit value. The EPR limit control was designed primarily to permit use of maximum permissible thrust during takeoff and go-around maneuvers with an automatic throttle system utilizing a single servo.

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LIST OF SYMBOLS, ABBREVIATIONS

A/P	- Autopilot
BAR	- Barometric Pressure
EGT	- Exhaust Gas Temperature
EPR	- Engine Pressure Ratio
FD	- Flight Director
g	- Gravitational Constant
GA/TO	- Go-Around/Take-Off
IAS	- Indicated Airspeed
ILS	- Instrument Landing System
K_D	- System Displacement Gain
K_{FU}	- Servo Follow-Up Gain
K_I	- System Integration Rate
$K_{\dot{u}}$	- Airspeed Rate Gain
$K_{\ddot{x}}$	- Acceleration Gain
K_{θ}	- Pitch Attitude Gain
MAN	- Manual
MRT	- Military Rated Thrust
NRT	- Normal Rated Thrust
PA	- Pre-Amplifier
Pt2	- Engine Inlet Pressure
Pt7	- Engine Output Pressure
RPM	- Revolutions per Minute
$\ddot{x}$	- Longitudinal Acceleration
$\ddot{x}_e$	- Longitudinal Acceleration due to Pitch Angle

LIST OF SYMBOLS, ABBREVIATIONS (Cont'd.)

u	-	Airspeed
u_a	-	Airspeed (Actual)
u_c	-	Airspeed (Command)
u_e	-	Airspeed Error
$\dot{u}$	-	Airspeed Rate
δe	-	Elevator Position
δT	-	Throttle Position
θ	-	Pitch Attitude

SECTION 1

INTRODUCTION

Present day cruise mode throttle systems are designed to control the throttle levers and in turn fuel flow about preset quadrant positions well within safe engine operating limits. An experimental throttle system, installed on a KC-135 aircraft, was designed to investigate power control in the more critical operating regions of takeoff and go-around, in addition to the cruise mode requirements. This system is described in Technical Report AFFDL-TR-70-164. One outcome of this flight evaluation was the takeoff limitation imposed when the maximum throttle lever limit was controlled as a function of position rather than by engine parameters. To overcome this limitation, the system described in AFFDL-TR-70-164 was modified to permit throttle limiting as a function of maximum permissible EPR. This configuration is described in the following text.

SECTION 2

ENGINE PRESSURE RATIO

2.1 ENGINE PERFORMANCE PARAMETERS (J57-P/F-59W ENGINE)

On the KC-135 aircraft, J57-P/F-59W power limitations are defined in terms of engine pressure ratio (EPR). This ratio of outlet pressure (P_{t7}) to engine inlet pressure (P_{t2}) is measured by a pneumatic device mounted on the engine. Performance parameters for this engine, as obtained during ground runs in a test cell, are given in Figure 1. The parameters have been plotted relative to throttle position for ease of reference.

2.2 PERFORMANCE LIMITING CONSIDERATIONS

Maximum safe engine thrust levels are a function of the engine inlet temperature. A typical curve of maximum EPR for any given inlet temperature is shown on Figure 2. To obtain maximum safe thrust for takeoff, one would obtain the ground level ambient temperature, refer to a curve similar to that in Figure 2 to obtain the limit EPR, and then advance the throttles until the desired EPR is obtained. The desirability for an EPR limit control rather than throttle position limit can be seen by noting that on an average day (55°F), an EPR limit of 2.50 is permissible (approximately 55° of throttle position from Figure 1); whereas, on a warm day (95°F), an EPR limit of only 2.25 is safe (approximately 47° of throttle position from Figure 1). While it is realized that an exact interpolation between throttle position and EPR cannot be made for various temperatures using ground data on one engine, the relation between EPR limit and throttle position limit in flight as functions of ambient temperature would be similar.

It should be noted that various auxiliary equipment consumes significant amounts of power requiring a subsequent reduction in the nominal stated engine EPR limit. As tabulated below, the nominal rated EPR must be reduced as follows for the specified auxiliary equipment.

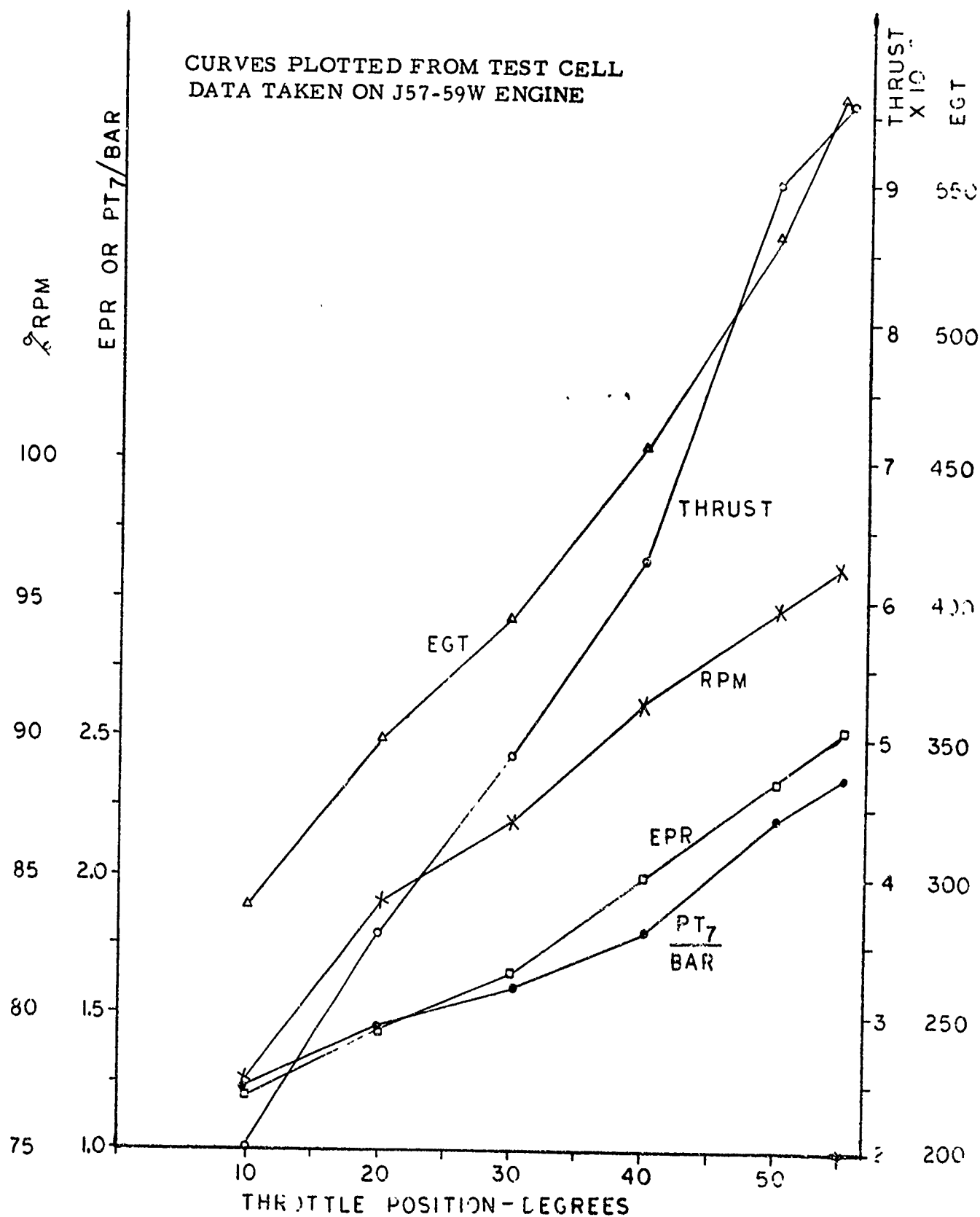


Figure 1. Engine Performance Parameters

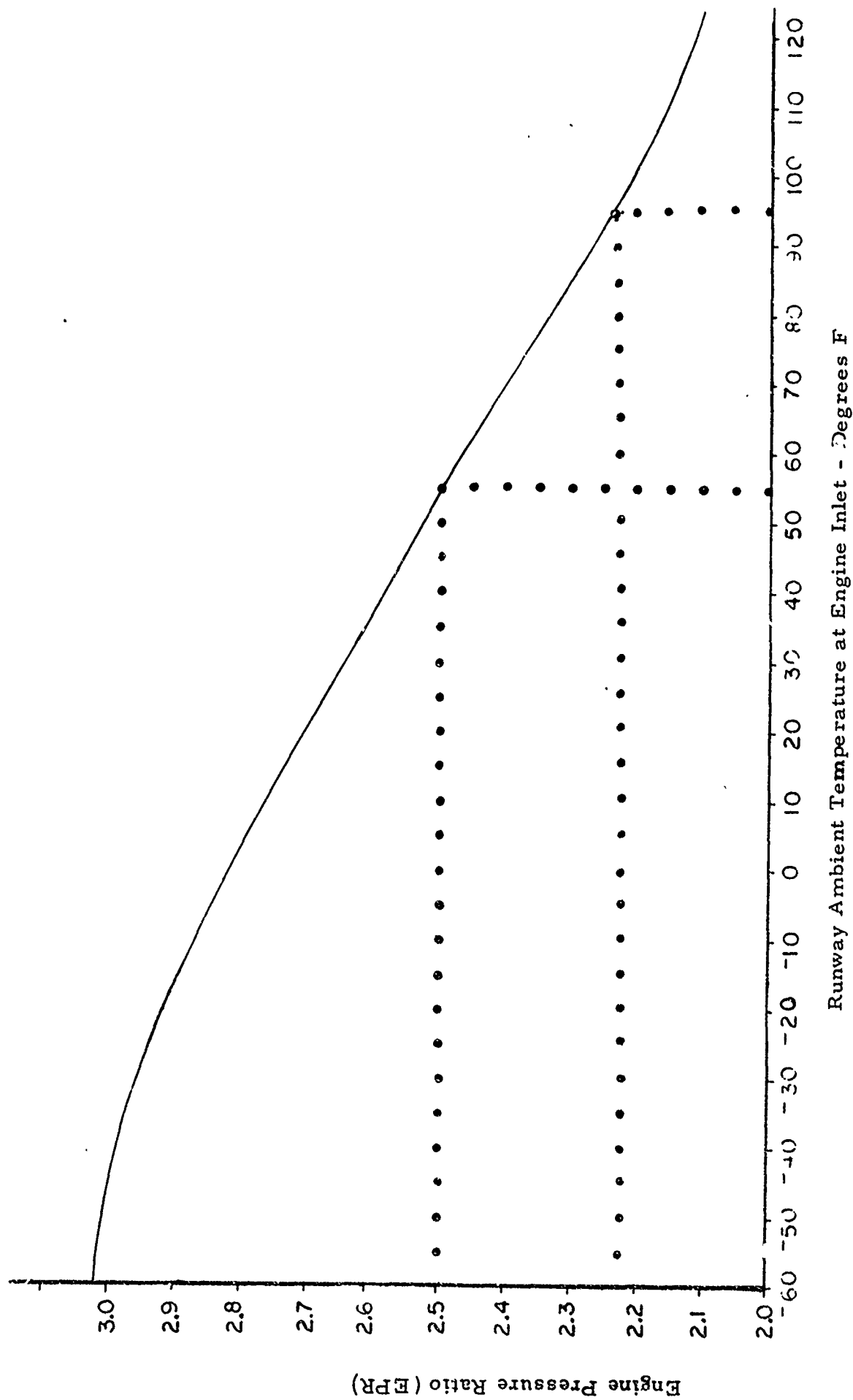


Figure 2. Takeoff Military Rated Thrust-No Water Injection

- (1) "Anti-Ice" - MRT minus 0.05 EPR
- (2) "Air Conditioning" - MRT minus 0.02 EPR
- (3) "Rain Removal" - MRT minus 0.01 EPR

The two categories of rated thrust normally used are "military" and "normal", designated MRT and NRT, respectively. The latter is a thrust rating for continuous operation and is nominally 0.26 EPR less than the MRT value. Military Rated Thrust is the power level permitted for 30 minutes of operation. Additional thrust categories such as Total Rated Thrust are available but are not considered within the scope of this report.

2.3 EPR ENGINE SENSING SYSTEM

The ratio of engine outlet pressure (P_{t7}) to engine inlet pressure (P_{t2}) is measured by a pneumatic device. A schematic of the typical sensing and display system is shown on Figure 3. Differential pressure is sensed within the transducer and recorded on a dual synchro system. The synchro outputs are transmitted to receiver autosyns mounted on the EPR readout gauge. The standard three-wire back-to-back autosyn transmitter-receiver configuration is as shown on Figure 3.

2.4 ENGINE EPR SIGNAL

In order to convert the three wire synchro data of the EPR transmitter for use in the control system, a motor driven back-to-back synchro system is used. A potentiometer attached to the motor shaft acts as the linear data source to produce voltages proportional to actual EPR. The ratio of potentiometer wiper rotation to synchro rotation has been selected so that, within the system's operating range, a point of ambiguity (0° or 360°) will not be encountered.

2.5 EPR LIMIT SENSING SYSTEM

The limit sensing system is an outside air temperature gauge with an EPR dial calibrated for MRT. A temperature probe on the side of the aircraft is the sensitive element with the remote readout available on the instrument panel. In addition to the dial readout, the instrument has a potentiometer that is separately excited to provide an analog voltage for use in this system. When the probe is exposed to direct sunlight with the

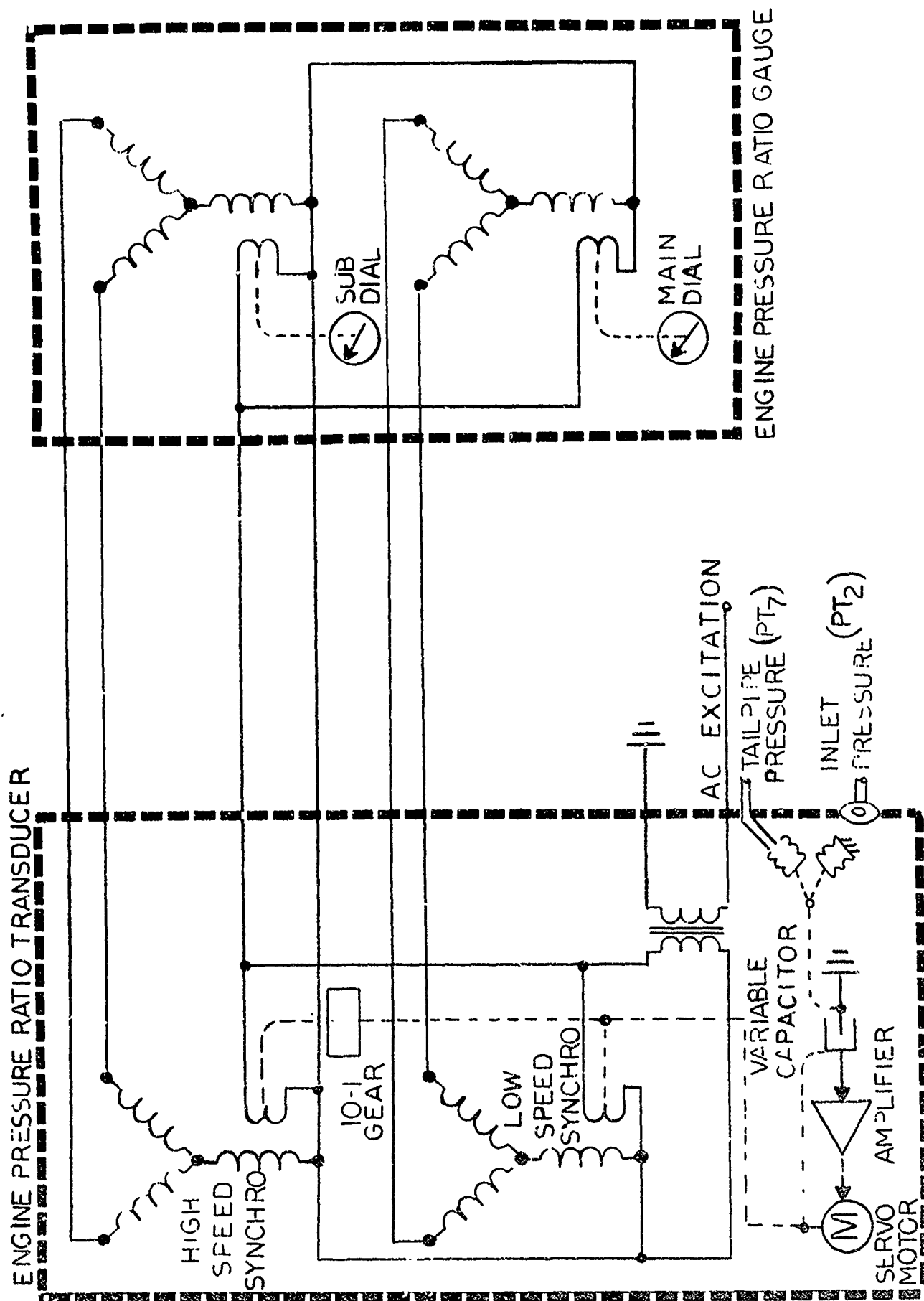


Figure 3. Engine Pressure Signal Schematic

aircraft stationary, the instrument registers heat absorbed due to sunlight as well as that due to the ambient air. To offset this discrepancy a manual EPR limit set capability is required. In this case, tower reported ambient temperatures are referenced to the EPR curves in the engine manual to establish the limit EPR. The limit EPR is then manually set into the system in lieu of the automatic limit provided by the temperature probe.

SECTION 3

SYSTEM OPERATION AND MECHANIZATION

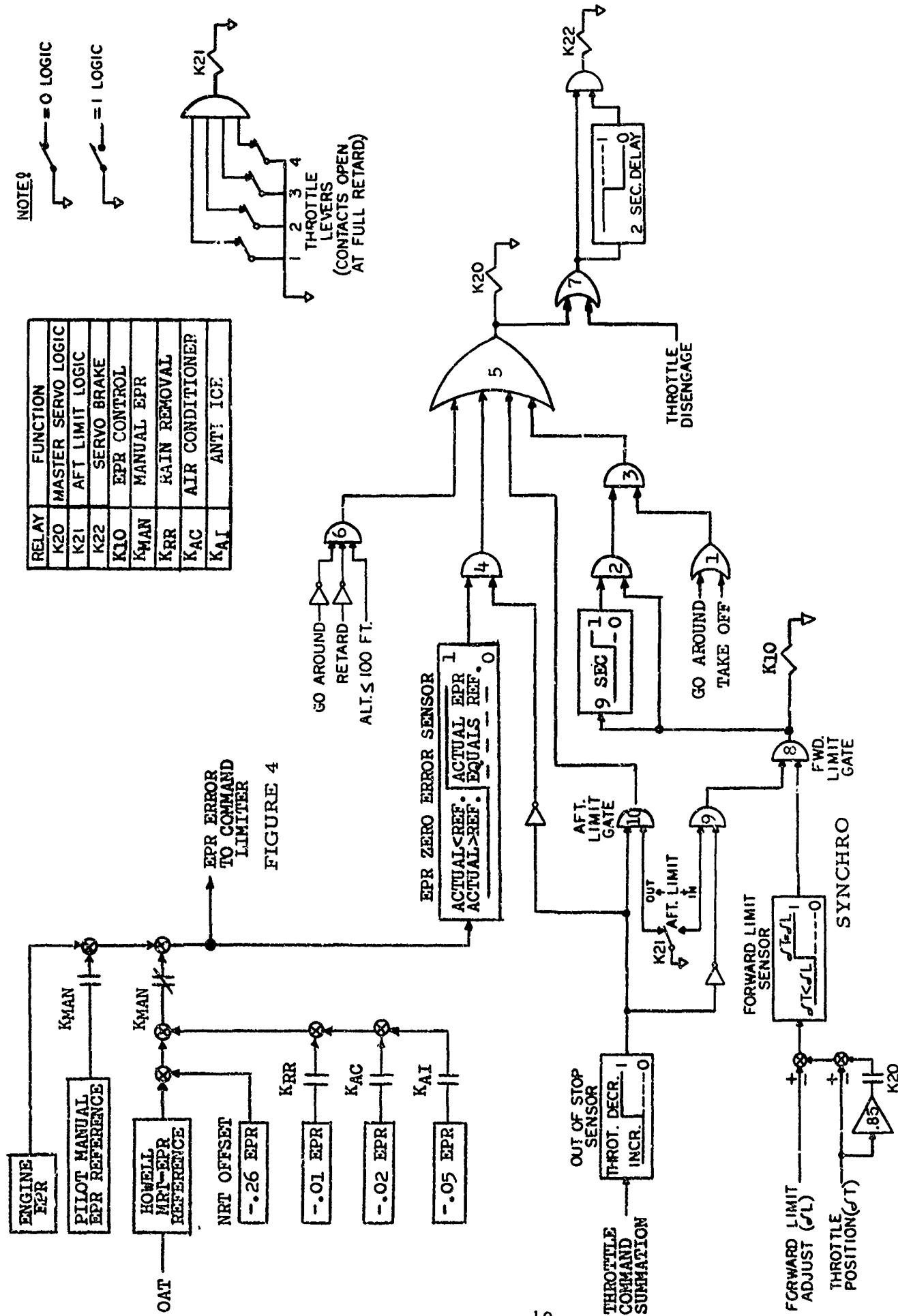
The integrated throttle control system has four pilot selectable modes of operation: Hold, Set, Manual, and Go-Around. The primary mode of operation is the Hold mode which is used for speed control during cruise, approach, and final. The Set mode is used only for takeoff and allows the pilot to pre-arm the throttle system for takeoff. The Manual mode permits pilot beeping of the levers in lieu of closed loop operation. The Go-Around mode and the throttle limit control are described in a later section of this report.

Figure 4 identifies the throttle system analogue control loops. The basic system controls the aircraft's throttle levers through a clutch pack mechanism that gangs the four throttle levers together to permit simultaneous response. The input power means to the clutch pack is a position type servo which responds to airspeed command errors as generated within the system signal chain.

Prior to incorporation of the EPR limit control into this system, the following three modes of operation used the throttle servo as a velocity controlled device as compared to the "Airspeed Hold" mode position servo configuration.

1. Landing/Flare - retard 5° /second
2. Takeoff - advance at 5° /second
3. Go-Around - advance at 20° /second

The EPR power limit technique incorporates a fourth velocity mode (2 to 3° /second) to establish go-around, takeoff and cruise/approach maximum power. The analog control and the dual level command rate limit (MRT, NRT) are shown in Figure 4, and the control logic is illustrated in Figure 5.



For clarity in the EPR limit discussion, a brief description of the go-around and takeoff modes follows. A detailed description of the modal operation of the throttle system to which the EPR power limit technique is applied can be found in AFFDL TR-70-164.

3.1 GO-AROUND AND TAKEOFF MODES

The Go-Around and Takeoff modes are actuated by pressing the go-around button located on the flight management control wheel. These two modes differ respectively in the rate at which the throttles are advanced, (20 degrees per second versus 5 degrees per second), the forward EPR limit value, (NRT versus MRT) and the mode engagement conditions, (airborne or ground roll versus stationary).

Actuation of the go-around button when in the approach airspeed hold configuration will result in a go-around throttle command. Actuation of this button operates relay K_4 (Figure 4) which eliminates the airspeed hold, preflare throttle freeze, and/or flare retard computation from the signal chain and introduces the go-around signal to the throttle servo (right hand side of Figure 4). The go-around signal drives the throttles to a go-around NRT power setting at a rate which affords safe operation with minimum altitude loss. The throttle rate chosen through flight test for the KC-135 vehicle is 18 to 22 degrees per second, as measured at the throttle quadrant. Upon reaching the approximate NRT limit position, vernier adjustment to the final value is accomplished at 2 to 3 degrees per second.

The Takeoff mode is armed by the selection of the Set mode, which energizes relay K_{23} . This eliminates all other modes from the signal chain and arms the system for a throttle rate of 5 degrees per second. Upon selection of the Set mode, engagement of the throttle servo, and actuation of the go-around button, the throttles will advance at a fixed rate to the pilot set MRT limit.

Both the Go-Around and Takeoff modes are disengaged by a second actuation of the go-around button. At this time, relay K_{20} (Figure 4) is de-energized, servo disengagement occurs, and the signal chain returns to its standard configuration. Upon re-engagement, the system will enter the Airspeed Hold mode.

In summary, the EPR limit system has two modes of operation, "Manual" and "NRT". The NRT mode (MRT-0.26) obtains its control reference from an outside air temperature gauge calibrated in engine pressure ratio. The manual mode employs a pilot operated knob to set the reference EPR. The latter may range from MRT for takeoff to an arbitrary limit below that for use in cruise operation. Of significance here is that for takeoff MRT operation, throttle lever position and engine trim vary between each engine to obtain the same EPR. Consequently, provision for manual engine trimming has been provided in this mode. Section 3.2.1 describes this operation through the use of the nine second delay circuit.

Takeoff Logic Example

- Gate (1) - 1 and 1 on the input to energize K10
- Gate (2) - Armed by Gate (8) and energized following completion of 9 second time delay.
- Gate (3) - Armed through Gate (1)
- Gate (5) - Energizes K20 Note: Should the EPR zero error sensor be satisfied prior to 9 seconds, Gate (5) will be energized through Gate (4).

K20 - Removes analog control permitting the servo inertia to hold the throttle levers in position through the clutch pack. Individual levers can then be trimmed relative to the friction clutch.

3.2 EPR LIMIT CONTROL LOGIC

The EPR throttle limit technique senses when the engines are close to their operational limit. A switching amplifier "Out of Stop Sensor" monitors the polarity of the throttle command, a Forward Limit Sensor monitors the difference between a safe forward throttle position and the actual throttle position, and an "EPR Zero Error Sensor" monitors the EPR error. A throttle limit is established during cruise conditions by the initial action of the Forward Limit Sensor. When the actual throttle position, as commanded by the throttle signal chain, is equal to a preset value, $\delta_T = \delta_L$, the Forward Limit Sensor logic is introduced to the Forward Limit Gate (8). When the Forward Limit Gate sees a $\delta_T = \delta_L$ condition, and a throttle increase condition, defined by Out of Stop Sensor and Gate (9), relay K10 is

energized. Relay K_{10} operates on the throttle signal chain (Figure 4) to insert the EPR command loop. The command signal continues to be monitored by the Out of Stop Sensor. The servo now operates on the EPR error at a rate defined by the EPR command limiter. The EPR Zero Error Sensor, which monitors the EPR error signal, introduces a logic signal to Gate 5 through Gate 4 when the actual EPR equals the referenced EPR. Gate 5 energizes relay K_{20} which decouples servo response from the EPR commands. K_{20} also causes relay K_{22} to change state, which in turn directs a d. c. voltage to the servo motor for a braking action, overcoming the motor and control system inertia. This braking action is applied for a period of two seconds, after which K_{22} returns to its normal state permitting the servo to respond to throttle commands provided Gate 4 has released Gate 5. When the Out of Stop Sensor sees a command for throttle decrease, or out of stop movement, the logic introduced to the forward limit gate (8) de-energizes relay K_{10} returning the servo to the cruise mode throttle command signal.

The EPR limit for cruise is established at NRT, the maximum power level at which the engines can be continuously operated. An EPR computer establishes this level. The EPR sensor used in conjunction with the test system is calibrated in MRT. For the operating range under consideration, the NRT thrust level is nominally 0.26 EPR less than the MRT value. The EPR compensation required for the MRT to NRT reduction and for rain removal, air conditioning and anti-ice accessories is accomplished in the auxiliary throttle computer as shown on Figure 5.

3.2.1 Go-Around Limit Control

The NRT EPR value is used to establish the go-around forward limit. The Out of Stop Sensor and Forward Limit Sensor logic operate in the same manner to establish the limit for Go-Around power as they do for the cruise condition. However, two additional logic inputs are required for Go-Around, (1) Activation of a Go-Around discrete by the pilot, and (2) a nine-second delay logic. Activation of the Go-Around discrete by the pilot arms Gate (3) and activates relay K_4 which eliminates the airspeed command signal from the signal chain and introduces a signal to advance the throttles at a fixed rate. As the throttles advance, the Forward Limit Sensor is activated and relay K_{10} is energized through Gate (8). Relay K_{10} modifies the throttle signal chain to permit vernier control of

the NRT limit. A delay circuit permits integration of EPR errors for nine seconds following actuation of the Forward Limit Sensor. Following the nine-second period, the two-second delay operates and the servo is braked and held at the forward NRT limit. A second activation of the go-around button during the go-around phase will disengage the system and decouple the throttles from the servo.

3.2.2 Takeoff Limit Control

The takeoff EPR limit design permits manual trimming of the engines by the pilot. This consideration is necessary since only one servo package is utilized for throttle control. In lieu of using the computed EPR data source as the control system reference, a manual means of inserting the EPR reference is used. Voltages from the EPR (MAN) reference potentiometer and the engine EPR transmitter are summed to provide an error signal to the EPR command limiter. The signal chain and the remainder of the system logic function in the same manner as defined for the go-around maneuver. Following the nine-second time delay, the pilot can manually trim each engine to the takeoff EPR value. For the Takeoff mode the maximum throttle rate attainable in the EPR limit region is three degrees per second. The Takeoff mode is disengaged by pilot activation of the go-around button. This pilot action disengages the system and decouples the servo from the throttle levers.

SECTION 4

RECOMMENDATIONS AND FINDINGS

The recommendations contained herein are based on program findings to date .

- 1) Accurate automatic EPR control for multiple engine aircraft would require either the same number of actuators as engines, or a clutching arrangement that would permit time sharing of one servo by several engines. The severity of the limitation imposed on takeoff performance, if any, when using one servo and one clutch pack, will be determined as flight time progresses.
- 2) An EPR reference system should be established that will be accurate for takeoff. One approach to this problem would be a digital readout of ambient outside air temperature telemetered to the aircraft from a tower or other ground station.
- 3) An automatic EPR limit readout should be part of the engine instrumentation.
- 4) For the single servo clutch pack configuration, EPR readouts should be made available for each engine. Actuator limiting could then be configured on a voter basis to permit system control to the most critical engine.

APPENDIX

PROGRAM PERSONNEL

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