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REON

ROCKET ENGINE OPERATIONS - NUCLEAR

REPORT NO. RN-S-0057

TO

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

DYNAMIC REQUIREMENTS

FOR

BLOCK I ENGINE CONTROL SYSTEM (U)

NERVA PROGRAM

CONTRACT SNP-1

FEBRUARY 1964

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DYNAMIC REQUIREMENTS
FOR
BLOCK I ENGINE CONTROL SYSTEM (U)

ROCKET ENGINE OPERATIONS - NUCLEAR

NERVA PROGRAM CONTRACT SNP-1 FEBRUARY 1964

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ABSTRACT

This report presents data that establishes the basic control requirements and nominal performance characteristics of Block I NERVA engines. These data supersede the data presented in report TM 738:63-207, "Dynamic Requirements for Block I Engine Control System," dated 25 September 1963. Data contained herein were derived through an analysis conducted on the power range analog model of the Block I engine. The model included a storage tank, turbopump assembly, nozzle, reflector, shield, reactor, and thrust chamber.

for W. D. Stinnett
REON Technical Systems Manager

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I. INTRODUCTION

This report is presented to establish the basic control requirements and the nominal performance characteristics of the Block I engine. This report is a formal revision of "Dynamic Requirements for Block I Engine Control System," TM 738:63-207, dated 25 September 1963. The analytical model used to establish these requirements was based upon present knowledge of the Block I engine configuration. The method of engine control used in the analysis is considered to be the best technique currently proposed. The feasibility of this system is, however, contingent upon the development of actual hardware which can meet the design requirements.

The analysis was conducted on the power range analog model of the Block I engine. This model included a storage tank, turbopump assembly, nozzle, reflector, shield, reactor, and thrust chamber. While the model represents a rather complete thermodynamic, flow and torque balance of the engine system, the two-phase flow simulation has not been completed and, therefore, was not included in the analysis. Since the two phase flow simulation was not included in the model, analysis of the boot-strap phase of operation is preliminary.

The control system dynamic requirements basically cover three aspects, namely; the control loop functions, the programmer sequencing, and the control loop compensations. The functions of the control loop establish the engine parameters that will be measured and controlled, and the general technique of controlling these parameters. The programmer sequencing establishes the method by which the engine may be brought to full power and shut down. Finally, the control loop compensations set forth the necessary component requirements to provide a stable and a responsive system.

Nominal performance capabilities are presented for all of the basic transient operations. Only those engine parameters of particular control interest were shown in the various transients. These engine transients were run with the control system utilizing the compensations established from the dynamic analysis. The transients demonstrate the capabilities of this control system to provide satisfactory engine performance.

Figure 1

Basic Control Loops and Control Components

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II. ENGINE CONTROL SYSTEM DESCRIPTION

A. GENERAL

The purpose of the engine control system is to perform control functions when command signals are transmitted from the engine programmer and thereby enable the engine to meet the necessary performance requirements. Upon command from the engine programmer, the engine control system will yield a smooth transition from one operating point to another within the desired time period. The engine programmer generates the demands to the engine control system based upon the commands of the ground test programmer. The engine programmer provides the sequencing logic necessary for the startup, steady-state, shut-down, cool-down, and restart of the engine.

The engine control system consists of three major feedback groups; the chamber temperature control loop, the chamber pressure control loop, and the neutron flux level control loop. These control loops are supplemented by the cool-down control system and the malfunction control system. The cool-down system controls the component temperatures resulting from fission product decay heating after a power shut-down. The malfunction control system is integrated with the engine and cool-down control systems in such a manner as to detect and control those unpredictable failures which might occur during engine operation. A block diagram of the engine programmer and control loops is presented in Figure 1.

A flow diagram of the engine is illustrated in Figure 2. Figure 3 is the same flow diagram transformed to a mathematical block diagram used in system analysis.

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Figure 2

Schematic of Propellant Feed System

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Engine Flow Diagram - Hot Bleed Diluent from Top of Shield

Figure 4

Block Diagram of the Temperature Control System

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B. TEMPERATURE CONTROL LOOP

The primary function of the temperature control loop is to maintain the chamber temperature demanded by the engine programmer. As a secondary function the loop provides the demand input to the flux loop described in Paragraph C.

A block diagram of the temperature control loop, including the transfer functions of the control components, is presented in Figure 4. The loop consists of the engine programmer demand signals, engine temperature control amplifier, flux control loop, the engine, thermocouples, and finally the temperature signal amplifier.

The loop operates either as an open loop controller or as a closed loop negative feedback system. As an open loop controller, the engine is adjusted by a proportional demand signal. In this mode of operation the system is subject to error since it is essentially a calibrated system. As a closed loop negative feedback system, the engine is adjusted by the error between its measured condition and the demanded condition. In this manner the system compensates for its own errors.

The engine programmer supplies the two demand signals for either open loop control or closed loop control. In Figure 4, the open loop demand signal is illustrated as the boot-strap nuclear power demand signal. The signal name is in reference to the open loop control during the turbopump boot-strap phase of engine operation. This signal increases the engine chamber temperature by increasing the reactor power level and must be a calibrated signal since it does not take into account the measured chamber conditions.

For closed loop negative feedback control, the programmer supplies a temperature demand signal which is summed with the negative feedback signal from the temperature signal amplifier. Summation of these two signals results in a temperature error signal. The proportional plus integral compensating network in the temperature control amplifier receives the error signal. The integral portion of this network makes the loop a zero error system. As long as an error exists, the compensation will integrate in one direction or the other depending upon the sign of the error.

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The output of the temperature control amplifier is the demanded flux level to the flux control loop. The reactor flux loop is a negative feedback system within itself and exists as a sub-loop within the temperature control loop. The reactor flux level is essentially proportional to the output power of the reactor. The chamber temperature is a function of the output power and the propellant flow rate. Therefore, the chamber temperature is controlled by the power level for a given flow condition.

Four or more temperature transducers are located in the thrust chamber and provide signals proportional to the gas temperature. The transducer signals are applied to the temperature signal amplifier. For reliability, transducer signals falling outside a given band are rejected by the system.

Figure 5

Block Diagram of the Nuclear Sub-loop

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C. NUCLEAR SUB-LOOP

The nuclear sub-loop has the primary function of controlling the reactor flux level. The flux level is programmed by the engine programmer during the sub-power startup and the open loop boot-strap phase. During the closed loop temperature control, the temperature loop provides the flux demand signal.

A block diagram of the nuclear sub-loop, including the transfer functions of the components, is presented in Figure 5. The loop consists of a flux demand signal supplied by the temperature control amplifier and the measured flux signal supplied by the flux detectors. These two signals provide the error signal which, when compensated by proportional-plus-integral compensation, yields the control drum position signal. The transfer functions of the flux loop were evaluated by WANL on the basis of the dynamic characteristics shown in WANL-TME-357. NDC-24A provides the design requirements by which the flux loop components will be upgraded, if required.

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Figure 6

Block Diagram of the Pressure Control System

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D. PRESSURE CONTROL LOOP

The pressure control loop has a primary function of maintaining the chamber pressure that is demanded by the engine programmer. Maintaining this demanded chamber pressure is accomplished by governing the torque of the turbine through regulation of the turbine power control valve. A block diagram of the pressure control loop, including the transfer functions of the loop components, is illustrated in Figure 6.

Chamber pressure signals are provided by two or more pressure transducers to supply measured pressure. These output signals are supplied to the pressure signal amplifier where they are averaged and amplified. The average measured pressure signal is generated by the same technique that is used for the temperature signals.

The average pressure signal from the pressure signal amplifier is supplied along with the demand signal from the engine programmer to the pressure control amplifier. The pressure control amplifier senses the difference or error between these two supplied signals and uses this difference as the driving error signal for the control of the turbine.

The position demand signal applied to the turbine power control valve (TPCV) actuator is generated by amplifying the error signal and supplying it through the compensation network in the pressure control amplifier. Through control of the turbine power, the feed system pressure is adjusted for any given demand signal.

When the temperature control loop receives a boot-strap valve position demand signal, the pressure control amplifier is bypassed, and the system operates in an open loop condition. (Refer to temperature control loop previously discussed in B.)

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E. COOL-DOWN CONTROL

The purpose of the cool-down control system is to dissipate the fission product decay heat generated after shut-down of a power run. Dissipating of this decay heat is accomplished by pulsing coolant through the engine system.

By the nature of the fission process, a quantity of delayed fission groups exist after operation of the reactor. These delayed groups decay by exponential functions and generate heat in the process of decaying. To prevent the components of the engine from overheating after the reactor has been shut-down, a flow of coolant is passed through the engine to extract the decay heat. The likely method for dissipating this heat is to pulse the coolant by means of an on-off valve at the storage tank. The control signal to the cool-down valve actuator will be initiated by temperature sensors located on critical components or locations. When the control temperature reaches a predetermined high limit the control system will open the cool-down valve, allowing coolant to flow through the system. When the control temperature reaches a predetermined low limit the control system will close the cool-down valve. Under present design concepts of the Block I engine, a likely control temperature would be the tie rod temperatures. A preliminary study of cool-down is reported in Reference 5.

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F. MALFUNCTION CONTROL

The malfunction control system has the primary purpose of providing override controls to the engine system as "fail safe" as possible. The malfunction control system is integrated with the engine programmer, engine control system and cool-down control system. In addition to the actual control circuits, the malfunction control is an extension of component and system reliability.

While work on the synthesis of the malfunction control system has been started, completion of this work could not be expected until the engine system has been more fully synthesized. A preliminary analysis of malfunction control is reported in Reference 6.

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III. ENGINE PERFORMANCE REQUIREMENTS

A. TRANSIENT OPERATION

1. General

The performance specifications are governed by the mission requirements, safety limits, and the component limitations. The mission requirements specify the engine thrust, total impulse, and the repeatability of these parameters. The component limitations include the maximum and minimum temperatures and pressures, maximum rates of change of temperatures and pressures, and other specific limitations. Safety limits specify the reactor control drum rates and reactor periods, and are governed by the ability of the control system to detect and control these parameters.

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Figure 7

Typical Subpower Startup Transient

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2. Subpower Startup

The subpower main startup brings the reactor to critical and then raises the power level to approximately 1 percent of design point power. Essentially, the reactor control drums are turned out at their maximum rate to a predetermined position, or turned at longer than 1.5 seconds, whichever occurs first. The reactor control drums are then turned out at a fixed slow rate until the reactor becomes critical. The power level is then raised on a pre-set period not faster than 1.0 second until the power level is approximately 1 percent of design point. The time for this transient should be approximately 40 seconds. Figure 7 illustrates a nominal subpower startup transient.

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3. Power Range Startup

The power range startup initiates propellant flow and raises the nuclear power until full thrust is obtained. The first phase of this transient depends on a boot-strap operation to start the turbopump. The second phase utilizes the power generated in the nuclear reactor to maintain propellant flow.

The boot-strap operation utilizes the latent energy of the engine components and depends upon the efficient deployment of this energy within the time cycle of the start operation. During this phase, propellant flow is characterized by two phase flow perturbations (Reference 4) which necessitates an open loop control. Reactor power is raised until the chamber temperature is approximately 1000°R , at which time the temperature control loop is closed. The turbine power control valve (TPCV) is programmed open by an open loop function until chamber pressure is 100 psia, at which time the pressure control loop is closed. Limitations affecting the boot-strap phase are:

- a. Reactor period may not be faster than 1.0 second.
- b. The core inlet temperature may not drop below 65°R .
- c. The rate of change in chamber temperature may not exceed $150^{\circ}\text{R}/\text{sec}$.
- d. The rate of change in chamber pressure may not exceed $40 \text{ psia}/\text{sec}$.
- e. The rate of change in chamber weight flow rate may not exceed $5 \text{ lb}/\text{sec}/\text{sec}$.

The closed loop power range startup begins when the temperature loop is closed. At this time, the log power demand is programmed by the temperature error signal. The temperature demand signal from the engine programmer is pre-set to a linear ramp of $100^{\circ}\text{R}/\text{sec}$. When the chamber pressure is 100 psia, the pressure loop closes and the TPCV is controlled by the pressure error signal. The engine programmer then brings the engine up to full power thrust. The temperature, flow rate, and pressure limits governing the boot-strap phase also apply to the closed loop phase of the power range startup.

Figure 8

Nominal Power Range Startup Transient

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Figure 8 illustrates a nominal power range startup transient. The first 10 seconds of the transient were used for pump chill-down. This is necessary in order to ensure that liquid hydrogen is contained in the pump when power is applied to the turbine. The 10-second time period for this chill-down phase is nominal, and used only for description purposes. Future analysis will determine a more accurate period of time. On completion of the chill-down, the reactor power was increased, and the TPCV was programmed open on the function illustrated in Figure 16. The chamber temperature was increased at $100^{\circ}\text{R}/\text{sec}$. The total time for this nominal startup transient to achieve steady-state design point conditions was 70 seconds; however, 95 percent of design point condition was achieved within 60 seconds.

The maximum allowable temperature of the reactor tie rods is 1000°R . Because of the flow characteristics of the core, the tie-rod temperatures can be controlled by maintaining a required flow or pressure at any given chamber temperature. For this reason, the temperature and pressure control loops are cross-coupled to provide the necessary $T_c - P_c$ relationship. Upon closure of the pressure control loop, the chamber pressure demand signal becomes a function of chamber temperature. This function is illustrated in Figure 17.

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Figure 9

Nominal Shutdown Transient

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4. Shut-Down

The shut-down control logic reduces the engine operating level from design point to a low level where the cool-down phase can begin. The chamber temperature is programmed down at a rate not to exceed $-150^{\circ}\text{R}/\text{sec}$. Chamber pressure follows a measured chamber temperature dependent function so that tie-rod temperatures do not exceed 1000°R . When the desired hold temperature is achieved, the temperature control is switched from nuclear power to the turbine power control valve (TPCV). At this point, chamber pressure is no longer controlled and nuclear power is reduced until the necessary flow conditions exist for the start of cool-down. Figure 9 illustrates a nominal shut-down transient. The chamber temperature was reduced at a rate of $-100^{\circ}\text{R}/\text{sec}$. Chamber pressure followed the dependent temperature function of Figure 17. When chamber temperature reached 1000°R , temperature control was switched to the TPCV, and the nuclear power was reduced on a controlled function. The time for the complete transient was 45 seconds.

Figure 10
Nominal Cool-Down Transient

5. Cool-Down

After completion of an engine shut-down, it is necessary to continue to cool the engine with propellant because of the residual heating caused by fission decay products. The cool-down phase maintains the engine temperatures within predetermined upper and lower levels. Control during this phase is maintained on measured component temperatures by pulsing coolant through the engine. The duration of the cool-down phase is a function of the time of a restart, or the time for fission product heating to decay out, whichever occurs first. A nominal cool-down transient is illustrated in Figure 10. Control during this transient was maintained on the measured tie-rod temperatures.

Figure 11

Chamber Conditions for a Normal Restart Transient

6. Power Range Restart

Restart of the engine is an added capability that would occur after a previous shut-down. The initial conditions, specifically, component temperatures, should be approximately the same whether the restart occurs initially after the shut-down or after the lapse of a cool-down period. Since a restart must boot-strap the turbopump, it is necessary to have the required heat capacity in the engine to start the turbine and, furthermore, not allow liquid hydrogen to enter the core. For this reason, a cool-down control system must be developed that will cool the reactor but will not sub-cool the reflector.

The first phase of the restart brings the reactor critical and increases the power level. When the reactor power level is approximately 3 percent of design point, the tank shutoff valve is opened and the turbine power control valve (TPCV) is programmed open. At the same time the temperature control loop is closed and chamber temperature programmed up on a linear function of $100^{\circ}\text{R}/\text{sec}$. When the chamber pressure reaches 100 psia, the pressure control loop closes and the pressure demand signal becomes a function of chamber temperature. The dynamic constraints during the restart are the same as during the initial startup.

Figure 11 illustrates the chamber conditions during a nominal power range restart transient. For the initial conditions of this restart it was assumed that the reflector had a component temperature of 100°R . The elapsed time for this transient was 35 seconds. Since the initial temperatures for a restart are much higher than those of the first startup of the engine, less time is required for the restart to achieve design point conditions.

TABLE 1

NOMINAL PERFORMANCE RATINGS AT STEADY STATE
VACUUM CONDITIONS

<u>Parameter</u>	<u>Symbol</u>	<u>Units</u>	<u>Rated Value</u>
Thrust, total engine	F	lb	56,350 $\pm 5\%$
Reactor power	P	Megawatts	1,120 $\begin{smallmatrix} +90 \\ -70 \end{smallmatrix}$
Chamber pressure, total nozzle inlet	P _c	psia	550 $\pm 5\%$
Chamber temperature, total, core exit	T _c	$^{\circ}$ R	4,090 $\pm 3\%$
Specific impulse, total engine (including turbine exhaust)	I _{sp_E}	sec	759 $\begin{smallmatrix} +19 \\ -27 \end{smallmatrix}$
Specific impulse, nozzle exhaust	I _{sp_e}	sec	779 ± 19.5
Specific impulse, turbine exhaust	I _{sp_{Te}}	sec	435 ± 11
Flow rate, propellant, total engine (including 0.75 lb/sec nominal bleed-off gas)	$\dot{W}_E$	lb/sec	75 $\begin{smallmatrix} +6.5 \\ -4.5 \end{smallmatrix}$
Flow rate, nozzle exhaust	$\dot{W}_e$	lb/sec	70 ± 4.1
Flow rate, turbine exhaust	$\dot{W}_{Te}$	lb/sec	4.25 $\begin{smallmatrix} +2.5 \\ -0.25 \end{smallmatrix}$

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B. STEADY-STATE OPERATION

During full power steady-state operation, it is necessary to maintain engine parameters within the values listed in Table 1. The maximum allowable temperature overshoot has not as yet been defined. However, an overshoot of 100°R above the allowable design point chamber temperature ($4090 + 3$ percent) is known to be safe and, therefore, this value will be used as the overshoot limit until a better definition is provided.

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IV. CONTROL COMPONENTS DYNAMIC REQUIREMENTS

A. FLUX LOOP

The dynamic characteristics of the flux loop were evaluated on the basis of those characteristics presented in WANL TME 357. The characteristics for the flux loop control components are illustrated in Figure 5. The design requirements, by which the flux loop components will be upgraded, if necessary, are provided in NDC 24A.

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Figure 12

Damping Ratio of Temperature Control Loop
As a Function of Thermocouple Time Constant

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B. TEMPERATURE CONTROL LOOP

The gains and compensation of the temperature control amplifier were adjusted to achieve a minimum time to design point steady-state conditions from startup conditions. This required a compromise between response at design point to small steps in temperature demand and the minimization of the asymptotic approach of temperature to design point under startup conditions.

The thermocouple response used in this evaluation was 0.3 seconds at design point. With this thermocouple, the temperature loop had a damping ratio of 0.53. Figure 12 presents a plot of the temperature loop damping ratio as a function of the thermocouple time constant. From this illustration it can be seen that the damping ratio would be reduced to 0.30 if the thermocouple time constant were increased to a half second. However, the damping ratio would be increased by adjustment of the control compensation.

The dynamic requirements of the temperature control system components are derived from the gains and compensation illustrated in Figure 4, and based upon a log N demand voltage of 10 at design point.

$$\frac{\log N \text{ demand}}{T_c} = \frac{2.30 \times 10^{-3}}{S} (1 + 3.33S) \quad \text{volts/}^{\circ}\text{R sec}$$

1. Temperature Signal Amplifier

Using 10 volts as the level of temperature demand voltage at design point, the gain of the temperature loop signal amplifier is 300 based upon the thermocouple calibration illustrated in Figure 13. The bandwidth of the signal amplifier, including the averaging circuitry, is required to be greater than 15 cps to prevent adding additional phase shift to the temperature loop because of electronic characteristics.

2. Temperature Control Amplifier

Using 10 volts as the level of the log N demand signal at design point, a gain of 300 V/V for the temperature signal amplifier and a D.C. gain of 8×10^{-6} V/ $^{\circ}$ R for the thermocouple, the D.C. gain of the temperature control amplifier becomes 0.96. The overall response of the temperature control amplifier is then:

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Figure 13

Thermal EMF of W-5RE/W-26RE Thermocouples

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$$\frac{\log N \text{ demand (volts)}}{T_c \text{ error (volts)}} = \frac{0.96 (1 + 3.33 S)}{S}$$

3. Variable Gain Control

Consideration should be given to the design of a variable gain temperature control amplifier. This gain should be varied as a linear function of measured temperature with the design point gain of 0.96, as indicated above. The gain at 1000°R should be about 1/4 of design point or about 0.24. This variable gain may be necessary to maintain stability at lower power levels under some malfunction conditions, and to ensure smooth startup and shut-down transients.

Figure 14

TPCV to Chamber Pressure Gain at Design Point

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C. PRESSURE CONTROL LOOP

The gain and compensation of the chamber pressure control loop were adjusted to achieve satisfactory performance during startup and at design point operation. The following transfer characteristics were established:

$$\frac{\theta_{\text{TPCV}}}{P_c} = \frac{1.0 (1 + 0.7S)}{S} \quad \text{degree/psi sec}$$

1. Pressure Signal Amplifier

Based on a pressure command voltage of 10 volts at design point, and a pressure transducer having a gain of 0.008 volts/psi, the gain of the pressure signal amplifier becomes 2.27. The bandwidth of this amplifier, combined with the pressure transducer output averaging circuit, should not be less than 15 cps.

2. Pressure Control Amplifier

The pressure control amplifier which provides the command voltage for the turbine power control valve (TPCV) actuator must generate 4.36 volts at design point operation corresponding to 43.6 degrees of valve angle. The gain and compensation characteristics of the pressure control amplifier become:

$$\frac{\theta_{\text{command}} (\text{volts})}{P_c \text{ error} (\text{volts})} = \frac{5.4 (1 + 0.7S)}{S}$$

3. Turbine Power Control Valve (TPCV) Actuator

The TPCV actuator characteristics used in arriving at the gain and compensation for the pressure control loop can be approximated as follows:

$$\frac{\theta_{\text{out}} (\text{degrees})}{\theta_{\text{demand}} (\text{volts})} = \frac{10}{0.0004 S^2 + 0.02 S + 1}$$

with a velocity limit of 350°/sec. This approximation is consistent with test data and hardware tie-in evaluation.

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The minimum resolution requirements of the TPCV actuator can be determined from Figure 14. Using the chamber pressure tolerance requirements of ± 25 psia, the TPCV actuator resolution would have to be 0.8° . This indicates that the TPCV actuator design resolution of 0.5° is a realistic design requirement.

Figure 15

Controls Schematic for Power Range Startup
Block I-E Engine

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D. ENGINE PROGRAMMER

The engine programmer provides the electrical functions necessary to sequence the engine control system through all phases of engine operation. It generates the command voltages to each of the control loops, and contains logic circuitry to provide malfunction compensation.

Figure 15 is a schematic of the engine programmer functions that are required to sequence the engine after tank shut-off valve (TSOV) opening. This schematic does not contain the nuclear startup or shut-down portion of the engine programmer function.

On the startup command, a time dependent voltage is applied to function F_3 which generates the initial log N demand voltage. When the measured temperature is equal to the preset temperature loop closure value, relay K_2 will close. The temperature control loop is then closed and the flux control loop becomes an inner loop of the temperature control loop.

The open loop pressure control is actuated when the time relay K_1 closes. The exact time of closure of this relay is dependent upon the pump chill-down characteristics, and will remain undefined until the cold flow development test system (CFDTS) tests are conducted. When relay K_1 closes a step command of 20 degrees is applied to the turbine power control valve (TPCV) actuator in addition to the time dependent TPCV position demand of function F_2 (illustrated in Figure 16).

When the measured chamber temperature is 1000°R , relay K_2 closes. The temperature demand signal is then increased on a ramp, equivalent to $100^{\circ}\text{R}/\text{sec}$ up to design point.

When the measured chamber pressure is 100 psia, relay K_3 closes. This closes the pressure control loop and then the pressure demand signal becomes a function F_1 (illustrated in Figure 17) of the measured chamber temperature.

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Figure 16

Open Loop TPCV Startup Function, F_2

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F. MALFUNCTION CONTROL

The malfunction control system has the primary purpose of providing override controls to the engine system as "fail safe" as possible. The malfunction control system is integrated with the engine programmer, engine control system and cool-down control system. In addition to the actual control circuits, the malfunction control is an extension of component and system reliability.

While work on the synthesis of the malfunction control system has been started, completion of this work could not be expected until the engine system has been more fully synthesized. A preliminary analysis of malfunction control is reported in Reference 6.

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V. CONCLUSIONS AND RECOMMENDATIONS

The requirements and capabilities of the control system presented in this report are based upon qualitative representation of the Block I engine as an analog computer model. Refinements will be necessary before the control system can be made operational. To achieve these refinements, a more detailed analysis of the dynamics of the engine system is being conducted.

Development of a detailed dynamic model will not only require a sophisticated mathematical approach, but also will require data correlation between theory and test. Data correlation will serve to upgrade the mathematical models, and to verify analytical results. Two problem areas in which more sophisticated models are being developed are (a) the two-phase flow of cryogenic hydrogen, and (b) pump characteristics in gas and two-phase mediums.

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