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EVALUATION OF ALTERNATE CONTROLS
FOR THE TECHNOLOGY ENGINE

JULY 1966

NERVA PROGRAM

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AEROJET

GENERAL

REPORT NO. RN-S-0304

**EVALUATION OF ALTERNATE CONTROLS
FOR THE TECHNOLOGY ENGINE**

JULY 1966

ROCKET ENGINE OPERATIONS - NUCLEAR

NERVA PROGRAM

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ABSTRACT

This report briefly describes studies that have been made for alternate NERVA control systems and compares them with systems already employed. The purpose of all studies was to achieve both a simpler and better performing control system.

The NERVA engine is limited to control by two methods: changing reactivity and turbine power throttling. The several variables and three options within these constraints are discussed. Primary concern in all systems is frequency response and stability. Both the effects of coupling and uncoupled performance are described, as are the phase and gain characteristics of a control system with the flux loop removed.

Emphasis is given to a modified temperature control (similar to the system employed for Phoebus testing), pressure control by drum motion, and to fixed drum control systems. The advantages and disadvantages of each are cited. Also discussed are the effect of startup and shutdown transients and the use of a closed-power-loop during transient conditions. For startup, a fuel-temperature controller is described as best: for shutdown, the best system is seen to be temperature control of the TPCV after scram.

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I. INTRODUCTION

This report evaluates the various control methods that are achievable on the basis of the technology engine design and instrumentation capabilities. The control system performance predictions for the NRX/EST (based on the CAM II analog model) are used as a standard for comparison of the alternate control methods. In addition to the evaluation covered in this report there are two main requirements to be defined prior to determining a final control system design:

1. Variables that are to be controlled.
2. The accuracy (both dynamic and static) to which these variables must be controlled.

In the development of NERVA engine controls, these requirements have never been sufficiently defined. In addition, requirements for a flight engine and for a ground engine are different in many respects. The flight engine control system is required to maintain a maximum I_{sp} at a specific thrust level. The ground-test engine control system is more oriented towards; (1) achieving a maximum operating temperature and nominal chamber pressure within the restrictions of safe operation and multiple restarts; and (2) to demonstrate controlled engine operation at various operating conditions.

To adequately define performance requirements for flight control, it is necessary to first perform a mission-oriented flight analysis to establish the I_{sp} and thrust requirements during startup, shutdown, and at required steady-state conditions. These, when combined with engine-system constraints, form a basis for specifying the overall control system requirements for the engine system.

This report does not make a selection of a control system but rather provides a comparison of control systems and a summary of characteristics of each system as tested in the breadboard technology engine (EST) and as applied to the flight arrangement technology engine (XE-1). When the overall control system requirements are defined for a flight engine and the characteristics of the NERVA engine are known, then a selection can be made.

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II. CONTROL METHODS

A. CONTROL MEANS

The NERVA engine is limited to two means of control: (1) control through changing reactivity; and (2) control through throttling power to the turbine. Therefore, this engine system essentially has two degrees of freedom. All control methods must ultimately reduce to control of reactivity and turbine power.

B. CONTROL VARIABLES

Control may be achieved on the basis of a number of system variables. To provide a reliable and accurate control these must relate to a direct measurement of the key parameters that need to be controlled. The basic two are: (1) thrust-chamber temperature, which is directly related to I_{sp} ; and (2) thrust-chamber pressure which is directly related to thrust. It has been demonstrated that chamber pressure and chamber temperature can be accurately and reliably measured and controlled. Considerations of other control variables for a NERVA engine have been reduced to a minimum except for consideration of inner loops to achieve a system that responds faster and is more stable.

C. CONTROL OPTIONS

There are three primary ways to control the two basic methods:

1. The first way is to control chamber temperature by control-drum movement, and control chamber pressure by turbine-valve movement. The variations on this first system are to have a flux loop (or other temperature loop) as an inner loop of the chamber-temperature loop, and then to couple these loops either by making temperature demand a function of measured pressure, or pressure demand a function of measured temperature.

2. The second control option is to make reactivity a function of chamber pressure and turbine throttling a function of chamber temperature. This method also has the coupling options mentioned immediately above.

3. The third method is to control the system in a "quasi open-loop" fashion by taking advantage of its internal dynamics: i.e., by controlling power with fixed drums through reactivity feedback from flow and temperature. This allows power to be increased either by closing the pressure loop and demanding a pressure ramp (thus increasing flow), or by manually programming the TPCV to provide a pressure change. Because of the inaccuracy of calibrating the engine, trim is necessary (by moving the drums and altering the TPCV setting) to achieve a desired operating point.

D. CONTROL COMPONENTS

Variations on the three basic control options can be accomplished by nonlinear actuation systems for reactivity and turbine power control. These, in turn, can be achieved by using "on-off" control mechanisms or digital-type control components. Consideration of these alternate control components presents a minor variation on the dynamics of linear actuation systems.

III. CONTROL EVALUATION

This section of the report is primarily concerned with the frequency response and stability of the various control systems. Section IV will discuss scheduling, startup, and shutdown problems associated with the various methods.

A. ESTABLISHED CONTROL SYSTEM

Figure 1 is a block diagram of the NRX/EST control system, in the uncoupled mode, which uses a closed flux-loop to control power by moving the drums. The flux loop then is an interloop of the chamber-temperature loop. The TPCV is driven by the controller which compares chamber pressure against chamber-pressure demand. This is the basic system used since the beginning of the NERVA program.

Figure 2 shows the frequency responses of the temperature-control loop, the pressure-control loop, and the flux-control loop used in this system. The 90° phase points for the loops are: pressure loop, 1.2 cps; temperature loop, 0.2 cps; and flux loop, 6.3 cps. All loops show good damping characteristics.

B. EFFECTS OF COUPLING

Figure 3 is a schematic of the established control system, showing two methods of control-loop coupling. The solid lines show the generation of pressure demand as a function of measured temperature. The dash lines show the generation of temperature demand as a function of measured pressure.

Figure 4 is a Bode plot showing the ratio of chamber pressure to chamber-pressure demand for the two methods of coupling, compared to the frequency response of the uncoupled system. For this comparison, perturbation of the chamber-pressure demand (in the coupling where pressure demand is a function of measured temperature) acts as a disturbance to the system: whereas, the other two are the direct action of the demand signal. There is considerable peaking (15 db at 4 cps). of pressure when temperature demand is a function of measured pressure.*

* This effect, it should be noted, is also shown in Figure 7.

Figure 1
Established Control System Schematic, Uncoupled Mode

Figure 2
Frequency Response of Basic Control System at Design Point Conditions

Figure 3
Established Control System Schematic

Figure 4
Frequency Response of Pressure Controller

The coupling in which pressure demand is a function of temperature shows some low-frequency "droop", a small amount of intermediate frequency peaking, and a higher bandwidth and less phase shift at the higher frequencies than do the other two control methods. The 90° phase points for the three pressure systems are: uncoupled, 1.2 cps; $T_{CD} = f(P_{cm})$ 0.6 cps; and $P_{CD} = f(T_{cm})$ 1.6 cps.

The next Bode plot, Figure 5, shows T_g measured over T_g demand for the three methods of coupling. The coupling in which temperature demand is a function of measured pressure shows more dipping in the intermediate frequencies and a higher peak at the higher frequencies. The phase plots also show this dipping and peaking effect in the coupling method in which temperature demand is a function-measured pressure. Uncoupled performance is more closely approximated by the coupling in which pressure demand is a function of measured temperature with some overall increase in frequency response.

The Nichols chart, Figure 6, shows the effect of peaking of the pressure loop in the coupling method in which chamber temperature is a function of measured pressure. It also shows about a 10° phase margin and 16-db gain margin for this method. The phase margin for the coupling method in which pressure demand is a function of measured temperature is about 60°; however, the gain margin is reduced and is about 11 db as compared to the uncoupled phase and gain margins of 78° and 18 db, respectively.

The next Nichols chart, Figure 7, shows the temperature-loop response for the various methods of coupling. The coupling method in which chamber-pressure demand is a function of measured temperature shows a phase margin of 80° and a gain margin of about 20 db. For the coupling method in which temperature demand is a function of measured pressure the phase margin is 88° and the gain margin is 20 db.

The two methods of coupling show the greatest effect in the pressure loop. The coupling of $T_{CD} = f(P_{cm})$ produces a very lightly damped pressure loop with reduced bandwidth. $P_{CD} = f(T_{cm})$ shows an improved performance over the uncoupled system.

Figure 5
Frequency Response of Temperature Controller

Figure 6
Pressure Loop Response

The coupling methods have less effect on the temperature loop and do not exhibit any marked improvements or disadvantages. However, the rapid changes in phase exhibited by the coupled systems at 0.08 to 1.6 cps indicate a system sensitivity which is less desirable than that exhibited by the uncoupled system.

C. FLUX LOOP REMOVED

Figure 8 is a schematic of the control system with flux loop removed. The temperature controller provides the drum-actuator demand signal directly and has the advantage of fewer control components and improved stability. And temperature-loop bandwidth can be increased since reactivity effects (because of chamber temperature) now become effective as an inherent feedback stabilization.

Figure 9 shows the phase and gain characteristics to which the temperature controller must be designed. The transfer function, $\Delta T_{Om}/\Delta Q_D$, is the characteristic with the flux loop removed. $\Delta T_{Om}/\Delta n_{DEM}$ is the characteristic of the temperature system with the flux loop. As the figure demonstrates, there is more phase shift (about 30°) with the flux loop than without it. On this basis, a temperature controller can be improved by not using a flux-loop controller as an inner loop.

D. MODIFIED TEMPERATURE CONTROL SYSTEM

The control system shown in Figure 10 is similar to the temperature controller that will be used on the next Phoebus experiment in which fuel-element temperature is measured directly and used for temperature control. This controller has the advantage of a wider bandwidth because of the sensitivity of fuel-element temperature to changes in power. Fuel-element temperature will more effectively control power at low temperatures and provide the proper phasing between auto start-up and the point of sensible temperature increase in the core.

It is advantageous to provide a direct control of I_{SP} for flight engine applications. This can be done by placing a chamber-temperature trim loop

Figure 8
Control System Schematic - Flux Loop Removed

Figure 9
Frequency Response at Design Point with Control Loops Open

Figure 10
Control System Schematic - Fuel Temperature Control With T_c Trim

around the fuel-temperature control loop and by providing a correction to the fuel-temperature demand to maximize I_{sp} near the design operating point.

Figure 11 is a Bode plot showing the increased bandwidth of fuel temperature as a function of drum motion, compared with the bandwidth of chamber temperature as a function of drum motion. Assuming 0.2 sec for the fuel-temperature thermocouple time-constant, the response of measured fuel temperatures is three times faster than that of the measured chamber temperature.

Figure 12 is a Nichols chart of the fuel-temperature control loop and shows a bandwidth at design point of 0.6 cps, as compared to the 0.2 cps bandwidth achievable with the chamber-temperature controller.*

E. PRESSURE CONTROL BY DRUM MOTION

Figure 13 is a schematic of a control system in which chamber-pressure error is used to provide drum-actuator demand: temperature error is used to drive the TPCV. This control method is shown to illustrate the degree of inherent cross-coupling within the engine by demonstrating that the system could actually be controlled in this manner: however, it is not considered a suitable control method because of reduced bandwidth when compared to the reference controller.

Figure 14 is a Bode plot comparing the function T_8/θ_v to T_8/θ_D . The general gain and phase characteristics are close together with the function T_8/θ_v being slightly degraded. The temperature loop, using valve motion as a controlling function, would have similar characteristics to that system which uses drums as a controlling function but it would possess reduced bandwidth.

Figure 15 is a Nichols chart showing pressure-loop response with drums as a controlling function. Compensating for this control loop is more difficult, however, because of the drop-off in gain and phase at about 0.4 cps that occurs in the function P_8/θ_D . This reflects in the closed-loop response as shown in the Nichols chart.

* The fuel temperature controller was not optimized and is overdamped as shown. Additional studies could improve the performance.

Figure 11
 Response Comparison of T_c to Fuel Temperature as Functions of
 Drum Motion

Figure 12

Fuel - Temperature Control Loop Response

Figure 13
Control System Schematic - Drums Control P_c , TPCV Controls T_c

Figure 14
 Frequency Response Comparison
 T_8 / Drum Demand to T_8 / Valve Demand

Figure 15
Pressure Loop Response

F. FIXED DRUM CONTROL SYSTEM

Figure 16 is a schematic showing a fixed-drum control system in which the chamber-pressure control loop is closed and pressure demand ramped to initiate an increase of flow through the reactor. The propellant coefficient-of-reactivity causes the reactor power to rise. A stable operating point is achieved when the temperature coefficient-of-reactivity balances the flow coefficient-of-reactivity at the fixed drum position. This system has been demonstrated to be a stable control method on both NRX/EST and NRX-A3. Its main advantage is that reactor power does not have to be scheduled and that the reactor system achieves its operating power inherently, preventing excessive temperatures being applied to structural elements. There are, however, several disadvantages to this method of control. One is the inability to accurately predict the reactivity coefficients. Another is that fuel element depletion during a run necessitates drum motion to balance the system at the desired power. A third is that an optimum I_{sp} startup along the structural temperature-limit line is not feasible.

Figure 17 is a Nichols chart showing pressure-loop dynamics for the fixed-drum condition. The chart shows the stability to be about the same at 32% power as at the 100% power point.

A similar startup can be achieved by using fixed-drum control and by manually opening the TPCV to a fixed position to achieve operating power. This has an additional disadvantage of requiring good calibration of the feed system to achieve the desired operating point. Otherwise, a trim control is necessary.

Figure 16
Fixed - Drum Control System Schematic

Figure 17
Pressure Loop Response, Fixed Drums

IV. CONTROLS SCHEDULING

Previous sections discussed various control stability studies in which small perturbations were introduced about a steady-state point. To complete the alternate controls evaluation, the effect of transients which occur during startup and shutdown are considered here. These transients occur when power is programmed from source level to the intermediate power hold, while temperature is simultaneously programmed from ambient design-point temperature and flow is programmed from zero-flow to full-flow conditions. The transients include the effect of initial flow when the propellant shutoff valve is opened and the effect of the initial turbopump bootstrap on the overall startup transient. The major shutdown transient of concern occurs when switching from the pump-supplied flow to tank-supplied cooldown flow.

A. DEMAND SCHEDULING

In the startup method used on NRX/EST, chamber-pressure demand was slaved to measured chamber temperature. The independent demand was the rate of power change. The power-demand schedule dominated the startup transient with the chamber-temperature controller providing an over-ride capability. This redundancy was required in early reactor tests because of uncertainty concerning the reliability of the temperature-measuring thermocouples. By having an independent power demand, the operator could "switch-out" the temperature-control loop and maintain control through the power loop. Since then, the thermocouples have proven to be reliable. Consequently, the requirements for independent power control have been eliminated. In addition, it has been demonstrated that effective power control can be maintained through manual drum-position control. The independent power demand will not be used for the X-E control system. Power demand for the higher power regions will only be provided as a result of the temperature-loop requirements.

B. CONTROL LOOP CLOSURE

In the process of going from source level to full power, the various control loops are closed and the flow through the system controlled. The control of

power during these transient conditions is most obviously accomplished by using a closed power-loop through a flux-level sensor. This power loop provides control over reactor power and prevents the various flow disturbances from upsetting the power schedule. While this an obvious method of power control it does not necessarily represent the best method because it requires an additional control loop and the overall system stability is reduced as discussed in Section III. Elimination of the flux loop can be achieved by programming the drums and using the rise in core temperature to initiate drum control.

Another problem associated with the transients is the closure of the temperature and pressure-control loops. Control studies performed before CFDTS and NRX/EST testing provided chamber-temperature loop closure at 1000°R and chamber-pressure loop closure at 50 psia. It has been found on the basis of the NRX/EST tests that chamber temperature and pressure transducers provided measurable signals at the initiation of flow from the propellant tank; thus, control loops can be started in the closed position. This eliminates the necessity of programming the TPCV and reactor power and closing the loop at a higher than ambient temperature and pressure point. Switching transients that might occur if the loops are closed when the value of the error signal is excessive can result in an undesirable transient. The lessening of reliability by using relays and electrical signals to close the loop is also eliminated.

C. STARTUP PERFORMANCE

A number of startup transients were run on the analog computer for the various control methods discussed in this report. While it was found that all methods can be made to perform startup within the allowable component constraints, the ease of achieving a smooth startup is dependent primarily on the "tightness" of the temperature and pressure-control loops at low power points. The temperature controller used on NRX/EST was very slow and lightly damped at the low power point.

Two approaches to achievement of better temperature-loop performance are presently being considered; (1) to operate with the flux loop removed; and (2) to control by measuring fuel temperature, as discussed in Section III.

The use of the fuel-temperature controller similar to the one to be tested on Phoebus IB provides the fastest startup transient and permits the optimization of I_{sp} by means of a fast startup. The chamber-temperature trim loop provides maximum I_{sp} at design point.

D. SHUTDOWN PERFORMANCE

The major shutdown problem occurs when the reactor is scrammed and cooldown flow switched from that provided by pump tail-off to that provided by tank pressure. The best method found analytically to make this a smooth transient is to switch from pressure control of the TPCV to temperature control of the TPCV after scram.* In this way, pump tail-off is controlled directly to bring core temperatures and flow to a point which matches available tank-pressure flow, thereby reducing the transient caused by the switchover to cooldown flow.

*This method was devised previously as a result of the flight engine studies.