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This memorandum is submitted in fulfillment of the January milestone of Paragraph F.4.d/4 in the Project 150 work statement. Documented within is the preliminary cooldown controls functional design and shows the status of the design effort to date. It does not represent completion of this effort. A description of the cool down phase of engine operation is also given, a preliminary cooldown control concept is defined, a cooldown control system functional block diagram and the resulting controller logic is presented. Some preliminary data obtained with the controller is also given.

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COOLDOWN CONTROLS FUNCTIONAL DESIGN

1.0 INTRODUCTION

The objective of the effort reported herein is to develop a controls design for the NERVA engine in the cooldown phase of operation which meets the performance requirements of References 1 and 6. This memorandum documents the preliminary cooldown controls functional design and shows the status of the design effort to date rather than the completion of this effort. The completion of this effort as outlined in the work statements will culminate in a first cut design which may not be optimized and which will not include any malfunction analysis.

A description of the cooldown phase of engine operation is given in Section 2, whereas Section 3 deals in some detail with the main topic of cooldown controls. The control concept is described, the control system functional block diagram and the controller logic are given and the cooldown predictor model is described. Section 4 shows some preliminary results obtained with the PRECUR model and the cooldown predictor model. Section 5 briefly states the conclusions and the work remaining to be done towards the development of the cooldown controller.

2.0 DESCRIPTION OF COOLDOWN OPERATION

Cooldown phase of the NERVA engine operation is initiated upon completion of engine shutdown and is completed upon termination of propellant flow or receipt of a command signal for restart. Cooldown operation from controls analysis standpoint may be divided into four distinct parts: (1) initiation of cooldown, (2) early cooldown (from start to about 2 mw), (3) low power cooldown (about 2 mw to 10 kw), and (4) cessation of cooldown.

2.1 INITIATION OF COOLDOWN

The cooldown initiation time is defined as the point of transition of pump tailoff to cooldown and is the point at which pump flow rate reaches

1.5 lbs/sec (LFI limit - if flow rate is less than 1.5 lbs/sec for over 300 secs, LFI condition will exist). When T_c of 1540°R is reached with this flow rate, the pump tailoff phase is terminated. At this time the turbine can be blocked and the coolant flow required to dissipate decay energy can be sustained by the propellant tank pressure head alone. TBVs are now shut and so also are the PDBVs. This shuts off the flow through the reflector and with the SSCVs and BCVs open, the flow through the stems is continued. Stem flow may be throttled with the BCVs as needed. When the pressure and flow perturbations caused by opening these valves have dissipated, the transition from pump tailoff to cool-down is considered complete.

2.2 EARLY COOLDOWN (FROM START TO ABOUT 2 mw)

This is the phase of cooldown during which there is continuous flow to the support stems with overlay (high flow - obtained by starting TPAs) pulses through the reflector, as required to maintain material limits. A flow schematic of the engine cooldown path is shown in Figures 1 and 2. Figure 1 shows the flow path at start of early cooldown at which time stem flow (~.43 lbs/sec) is the only flow to the reactor. The flow continues into the central plenum of the core support plate and through the structural support elements into the reflector exit plenum. From here onwards the flow continues along the normal engine flow path to the nozzle chamber. Figure 2 shows the flow path when the high flow overlay pulses through the reflector come on. The total flow (>1.5 lbs/sec) is split with a fraction of the total diverted through the SSCV/SSBV quad-pack, to cool the stems and the remainder through the nozzle tubes and reflector. The two flow streams combine at the reflector exit plenum and thereafter continue along the normal engine flow path. During the early cooldown phase, stems are limiting and as such a continuous flow is maintained to the structural support system. Stem limit is maintained by pulsing flow through the reflector path as required.

During early cooldown, the rate of temperature rise and the various temperatures will be used to estimate the decay power source term so that predictions of total impulse and duration made at the throttle hold can be updated.

If engine control, as a result of operating at high temperatures results in predicted total impulse less than the impulse demand from the guidance system, the guidance system may ask for a higher thrust to overcome this situation. This may be provided by either increasing the length of pulse

FLOW SCHEMATIC FOR 1137400E DESIGN

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FIGURE 1 NERVA E-ENGINE REFERENCE DESIGN FLOW SCHEMATIC

FLOW SCHEMATIC FOR 1137400E DESIGN

FIGURE 2 NERVA E-ENGINE REFERENCE DESIGN FLOW SCHEMATIC

duration or using higher flow rates during the pulse (it is assumed that the impulse maneuverability is sufficient to meet I_{dem}).

If, as a result of the new predictions, it is found that the impulse demand cannot be met without an unacceptable penalty in specific impulse the cooldown controller will call for an idle mode burn of sufficient duration to provide the required energy.

2.3 LOW POWER COOLDOWN (ABOUT 2 mw to 10 kw)

When reactor power decays below 2 mw, continuous stem cooling is no longer required and all engine components can be maintained within temperature limits by pulsing coolant through the reflector and stem simultaneously, Figure 3. During this phase of cooldown operation, reflector material temperature is limiting. The flow rate through the reflector is controlled by the throttling capability of the CSCV. The flow rate may be also influenced by the guidance system depending upon the closeness of the engine impulse from the impulse demand.

2.4 CESSATION OF COOLDOWN

Final cooldown pulse (quenching pulse) is initiated when decay power is down to 10 kw. This will lower the chamber temperature considerably (550°R) and since the power level is falling, overheating will not occur after termination of the quenching pulse. This quenching pulse is to allow simultaneous satisfaction of the $\pm 20,000$ lb-sec impulse controllability requirement and a requirement to predict cooldown termination time within ± 15 seconds. On cooldown termination, the CSCVs are shut and the engine is ready for coast.

3.0 COOLDOWN CONTROL SYSTEM

A preliminary cooldown control system is described in this section in order to satisfy an immediate goal of establishing a design approach. The ultimate goal of this study, however, is to develop a controls design which will allow the cooldown operation to be completed without violating any engine constraints and at the same time satisfying the cooldown control requirements.

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To describe the cooldown control system, a simplified block diagram of the concept is described in Section 3.1, a control system functional block diagram is described in Section 3.2, the detailed controller logic in Section 3.3 and the cooldown predictor model is described in Section 3.4.

3.1 COOLDOWN CONTROLS CONCEPT

A simplified block diagram of the proposed cooldown control system concept is shown in Figure 4. Three basic functions are considered which affect the valve demands to be sent to the engine.

1. Valve profile prediction, wherein the profile predictor, using previous engine history selects valve profiles for the k_{th} coolant pulse which satisfies guidance requirements and does not violate engine constraints in the k_{th} or $(k + 1)_{th}$ coolant pulse. The engine measurements from the $(k - 1)_{th}$ coolant pulse are used to improve profile prediction.

2. Total impulse prediction, wherein an evaluation is made as to the ability of the engine to meet the impulse demand. Based on the entire engine burn, the cooldown history and certain stage measurements, criteria for choosing valve profiles may be adjusted to impact on the profile calculator.

3. Profile correction, wherein valve profiles may be altered to prevent exceeding engine constraints, if the calculated profiles are inadequate. The calculated profiles are an open loop component of valve demands and the profile correction is a closed loop trim added to the open loop component.

3.2 CONTROL SYSTEM FUNCTIONAL BLOCK DIAGRAM

A detailed block diagram of the concept described in Figure 4, is shown in Figure 5, wherein the control system is considered to be composed of of basically two parts:

1. Short term control, which looks at the engine constraints and calculates the best valve profiles to keep the NSS from approaching the constraints.

2. Long term control, which looks at the impulse demand from the guidance system and compares with the modified predicted impulse to influence the valve calculation in order to satisfy the demand or influence the restart of the engine.

Figure 4
COOLDOWN CONTROL SYSTEM CONCEPT

FIGURE 5

COOLDOWN CONTROL SYSTEM
FUNCTIONAL BLOCK DIAGRAM

1. Short Term Control

The short term control system consists of a simulator, which is a simplified model and represents the cooldown phase of engine operation. The input to this block is burn time, time at throttle hold, tank pressure and initial valve profiles from past measurements. The simplified model, which runs faster than real time, computes the system profiles. If the system profiles violate the engine constraints, a new valve profile is next tried until no constraints are violated. This evaluation of the valve profile is performed by the block termed "Evaluation of Predicted Pulse", and feeds back into the predictor block via a block which calculates the valve profile for the next iteration. When no engine constraints are violated the calculated valve profile is fed to the engine as the "open loop" component of a valve command. The engine measurements are fed to the profile correction block where the comparison is made between the predicted system response and the measured system response. Information from this comparison is used to trim the open loop valve profiles, permitting operation close to the constraint lines without overshooting constraints. The comparison with measured and predicted performance is also used to improve the accuracy of the predictor.

A question also to be considered here is, how does the long term control influence the short term control? This influence is determined from the results of the impulse measurements made on the engine and the impulse predictions, as to how far or close we are from meeting the impulse demand required by the guidance system. This result will affect the evaluation of the pulse sent to the engine.

2. Long Term Control

The long term control system consists of a predictor which can, during the throttle hold make an initial prediction of the total impulse and thrust profiles prior to shutdown. The input to this block is burn time, time at throttle hold and other pertinent system variables. This information is sent to the update block where the originally predicted information is updated by the engine measurements which feed in from the short term control logic. Depending on the predictions, it may be decided to restart the engine if the impulse maneuverability is not sufficient to engulf the impulse demand. It is assumed that the hold at throttle point was such that no reverse thrust

is needed. The impulse demand from the guidance system and the updated impulse are fed to the block, "Evaluate Thrust and Impulse Profile", where the decision is made as to the influence this control system should exert on the short term control.

3.3 CONTROL SYSTEM LOGIC

The cooldown control system functional block diagram was described in Section 3.2. A preliminary logic diagram describing in greater detail the functions of each block in Figure 5 is described in this section. The overall cooldown control system logic is shown in Figure 6. On a command signal to initiate cooldown the following valves are opened fully: SSCVs, SSBVs, BCVs BBVs and PSOVs whereas PDBVs and TBVs are shut. Also in the full open position are PDCVs and CSCVs. At this time, dependent upon past engine measurements, initial valve profile Δ (stem flow only) or $\mathfrak{T}$ (reflector overlay pulse) is picked as a first guess to the profiles. In determining the valve profiles the procedure that is followed is to cycle the initial guess through the simplified model and change this guess until no engine constraints are violated up to the completion of a pulse and then send this valve demand to the engine before going on to the next pulse. As the engine operates on this open loop valve profile, the resulting system transients are continuously compared with predictions made in the iterative calculation of the open loop profiles. If a significant difference exists, the difference can be detected long before constraints are exceeded. A new time to reach a constraint is then computed by extrapolation of the measurements and Δ and/or $\mathfrak{T}$ is altered accordingly.

With the valve profiles picked for the first pulse, the next step is to initialize Δ and $\mathfrak{T}$ and set $\Delta = DD$ (10 secs) for the next set of valve profiles. When liner temperature is limiting, each flow pulse is at least 1.5 lbs/sec. If the reflector temperature is limiting as in low power cooldown, each flow pulse is less than 1. lb/sec. These flow rates are used in the simplified cooldown model for the lengths of time Δ and $\mathfrak{T}$ as determined by the profile predictor subject to NSS constraints.

Two additional factors need to be considered before sending the next predicted valve profile to the engine. (1) How did the engine respond to the previous valve prediction? If the constraints were exceeded then either length of time stem flow only existed is increased or length of time reflector

flow only is varied. These changes are accomplished by variation of the constants a and b in the logic diagram and this variation in the profile is cycled through the engine until no limits are exceeded. (2) By comparing the prediction of the impulse at the terminal time and the impulse demand from the guidance system, is any impulse correction needed? If impulse correction is needed, the constant b is varied. It is this total corrected valve profile that is next sent to the engine.

The control system discussed above pertains only to the phase of engine operation after leaving the pump tailoff (i.e., cooldown phase). The projection of total impulse from the throttle hold to the termination of cooldown is vital in order to accomplish the impulse demand required by the guidance system. Without this projection and the appropriate hold at the throttle point, the cooldown controls may not be able to accomplish its objectives.

Figure 6 also shows the computation of average engine I_{sp} , which is defined as:

$$I_{spav} = \frac{\int_{t_0}^{t_e} \dot{w} I_{sp} dt}{\int_{t_0}^{t_e} \dot{w} dt} = \frac{\text{Total Impulse}}{\text{Total Propellant}}$$

This information and the total impulse are needed to interact with the long term control (or for impulse correction). If the average I_{spav} is < 400 secs then a decision has to be made for a restart.

3.4 COOLDOWN PREDICTOR MODEL

The cooldown predictor model used here is an improvement on the two node model used in the FEP program (Reference 2). Two additional nodes namely, that of liner temperature and chamber temperature, have been added to the FEP model and the responses compared to the S-001 update data up to the first 800 secs into cooldown (Reference 3). The model and the comparison of important state variables with S-001 update data have been documented in Reference 4. The block diagram of the model is shown below:

The model is described by a set of seven linear differential equations, with four states shown above and three additional states representing the decay heat terms, namely Q_5 , Q_6 and Q_7 . The equations are written in a generalized form below:

$$\begin{bmatrix} \dot{T}_c \\ \dot{T}_R \\ \dot{A} \\ \dot{Q}_5 \\ \dot{Q}_6 \\ \dot{Q}_7 \\ \dot{T}_{CH} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} & A_{17} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} & A_{27} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ A_{71} & \vdots & \vdots & \vdots & \vdots & \vdots & A_{77} \end{bmatrix} \begin{bmatrix} T_c \\ T_R \\ A \\ Q_5 \\ Q_6 \\ Q_7 \\ T_{CH} \end{bmatrix}$$

The matrix of elements A 's includes all the flow rates, and other system components and an additional variability in certain elements, introduced to match the data.

4.0 PRELIMINARY RESULTS

The results presented in this section are those that were obtained on the cooldown predictor model, using the cooldown control system logic described in the previous section. The results were obtained on the Univac 1108 digital computer. The results obtained on the PRECUR model, showing impulse maneuverability have been presented in Reference 5 and hence will not be repeated here.

The cooldown control system logic is first used to generate the valve demands that were obtained in the S-001 update data. These valve demands were generated as a result of a trial and error process. The following rules of logic were used in early cooldown, in an effort to maximize T_c and minimize liner temperature overshoot.

1. Minimum duration of either the "on" or the "off" phase of reflector overlay pulses is 10 secs, regardless of T_c .
2. After 10 secs if $T_c < 1550^\circ R$, reflector pulse is terminated unless $\dot{T}_c$ is positive.
3. To avoid liner over temperature, the first reflector pulse is initiated when liner temperature is CRD, second pulse is initiated at TBD + $50^\circ R$, third at TBD + $100^\circ R$ and so on.

For the present simulator model the initial starting point is a set of initial conditions at the start of cooldown and a time interval Δ , say 10 secs during which we have stem flow only. After this time interval, the controller logic looks at the time response of the simulator and adds additional 10 secs to this condition if needed or initiates a flow pulse for τ sec. At the end of this flow pulse, another decision is made either to retain this pulse for additional 10 secs or go back to stem flow only case. Completion of one cycle through the controller constitutes time interval for stem flow only and time interval for overlay flow pulses in which no constraints are violated. This information is sent to the engine as the controller starts computation of another cycle of low flow and high flow pulses.

Figures 7 and 8 show the comparison of the predictor model with the S-001 update data in the first 550 secs into cooldown. Figure 7 shows the time plot of the material temperature A whereas Figure 8 is the time plot of the chamber temperature. Also shown in the figure are the valve profiles obtained by the use of the cooldown controller and the corresponding transient response of the variables. The logic used to initiate and terminate pulses is similar to that used in the S-001 update. Note that the valve profiles predicted by the controller are similar to those obtained in the S-001 results. Figures 9 and 10 are the time plots of the state variables A and chamber temperatures as a result of valve profiles predicted by the cooldown controller that do not violate the engine constraints in the early cooldown. Material temperature limit of variable A is not violated but past 300 secs the temperature is seen to depart from its limit. Chamber temperature on the other hand stays between $1500^\circ R$ and $1600^\circ R$ up to about 400 secs and drops to a lower value past this time. The average

TL 1350

TL 40 R

TH 1550

1800

Predicted Pulse

1700

FIGURE 7

PRELIMINARY DATA WITH PREDICTOR
MODEL TO GENERATE VALVE DEMANDS.

1600

COOLDOWN PREDICTOR
MODEL

1500

1400

1300

S-001 update data
(PAM Run)

Response due to
Predicted Pulse

1200

1100

1000

100

200

300

400

500

600

700

FROM START OF COOLDOWN

TIME (SECS)

1000

FIGURE 8
PRELIMINARY DATA WITH PREDICTOR
MODEL TO GENERATE VALVE DEMANDS
(Chamber Temp Response)

FROM START OF COOLDOWN.

FIGURE 9

VALVE DEMANDS PREDICTED BY COOLDOWN
CONTROLLER WITH NO NSS CONSTRAINTS EXCEEDED.
(MATERIAL TEMP RESPONSE)

FIGURE 10

VALVE DEMANDS PREDICTED BY COOLDOWN
CONTROLLER WITH NO NSS CONSTRAINTS EXCEEDED.
(CHAMBER TEMP RESPONSE)

Isp stays roughly at 500 secs. The logic past 300 secs needs therefore to be modified to either decrease the frequency of these overlay reflector pulses or shorten the width of the pulses. The results obtained look very encouraging and the valve profiles generated here will be tested on the CDM in due course of time.

5.0 CONCLUSIONS

The following conclusions can be arrived at in light of the material presented in the sections above:

1. The cooldown control concept has been defined and the control system functional block diagram has been prepared.
2. The predictor model to be used with the cooldown controller has been developed and is shown to check out in the first 500 secs into early cooldown.
3. The cooldown control system logic has been checked out with the predictor model to generate a set of valve demands to be used on the CDM and PAM in the early cooldown.

In light of the conclusions arrived at above, the following work is planned which will ultimately lead to the establishment of a functional design for the cooldown controller.

1. Check valve demands generated with the predictor model on the CDM and PAM and use the results to improve the predictor.
2. Study the effect of the long range control system logic on the valve demands.
3. Incorporate the control scheme in the CDM.
4. Study the controller responses to:
 - i. Various initial conditions at start of cooldown.
 - ii. Tank pressure variations
 - iii. Variation of time at throttle hold.

NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>
LFI	Laminar Flow Instability.
I_{dem}	Impulse demand from the guidance system.
Δ	Time between pulses (stem flow only).
τ	Time duration of a pulse (reflector overlay pulse).
DD	Unit by which time between pulses is varied to compute total Δ .
TTP	Unit by which time duration of a pulse is varied to compute total τ .
a	Fraction associated with correction of Δ towards profile correction.
b	Fraction associated with correction of τ towards profile correction or impulse correction.
Q	Total decay power. Sum of Q5, Q6 and Q7.
α	Fraction of total energy deposited in the core.
β	Fraction of total energy deposited in the reflector.
γ	Fraction of total energy deposited in the support stem liner.
A	NSS material temperature.

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