AEROJET NUCLEAR SYSTEMS COMPANY
SACRAMENTO, CALIFORNIA

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FROM: F. L. Openshaw/E. A. Parziale

SUBJECT: Startup Controls Design

DISTRIBUTION: C. R. Dippel, J. K. Saluja, R. F. Schenz, E. A. Sheridan

ENCLOSURE: (1) Status Report for Startup Reference Functional
Control System Design Effort

The startup control system design effort which began in June assumed a reference startup method which employed the powered chill approach during temperature conditioning. Due primarily to the high penalty in propellant utilization with this approach, the "pressure chill" concept has been proposed. This redefinition of the reference startup method has a major impact on present startup work and a revised work plan and schedule must be determined to reflect the change.

The purpose of this memorandum is to document the startup work done to date in accordance with the original work plan. The work plan and schedule are given with the work accomplished to date indicated. Documented within are the limited set of initial conditions which were to be considered in the first phase of the startup controls design work. A description of the startup supervisory logic, startup sequencing, and the startup digital control program are contained along with an ambient startup response employing analog controls and sequencing.

MASTER

F. L. Openshaw
F. L. Openshaw
C&I Section

E. A. Parziale
E. A. Parziale
Controls Analysis
NIICO

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1. STARTUP WORK PLAN

A block diagram of the overall startup control system design plan is given in Figure 1. All the steps leading to a reference functional startup design are shown with the work accomplished to date indicated.

Startup control requirements have been established and are given in Reference (1). The supervisory logic which determines the sequence of events during startup and the digital control program which implements this logic in conjunction with state feedback control calculations have been produced and will be discussed in subsequent sections. The supervisory logic is complete except for certain equations which establish sequencing criteria in the logic. These equations are presently being generated based on turbopump and nuclear subsystem analysis data. Once these equations are included in the digital program, initial digital control work will begin. At present, open loop analog runs are being made to investigate the control characteristics of the startup model and to check out the model implementation.

Indicated in the design plan diagram is a parallel effort to design state feedback controllers. This effort requires a TAF digital startup model as its starting point. Work is currently in progress to make the TAF startup model operational at which time TAF data will be obtained for use in the design programs.

The startup controls design activity schedule is given in Figure 2. A major delay has been introduced because of the unanticipated time to set the TAF program up on the IBM 360 system at Aerojet in Azusa. Also, certain necessary equation changes in the startup model have required reprogramming. In terms of analysis work being done on the hybrid model, an approximate two-week interruption is expected while the FIOP function generator is being incorporated into the hybrid model.

(1) "Design Requirements for Startup Control", F. L. Openshaw, N8630:5126M, 24 September 1971 (See Attachment 1)

*Work completed or in progress.

FIGURE 1
STARTUP CONTROL SYSTEM
DESIGN PLAN

ACTIVITY SCHEDULE SHEET

PROJECT NO. 150

PAGE 1 OF 1

PROJECT TITLE STARTUP CONTROLS DESIGN

DEPT MGR APPROVAL _____ DATE 10/13/71 REV NO. _____

- (1) Delay due to setting up TAF on new 360 system.
- (2) Delay in analysis work due to incorporation of FIOP into hybrid model.

*Overall activity subject to change due to:

- (a) Redefinition of reference startup method, or engine configuration (for example: This analysis assumes power chill; however tank pressure flow may possibly replace this)
- (b) Major startup model equation changes.
- (c) Availability of 360, 1108, and hybrid computer time.

FIGURE 2

The startup controls work plan and schedule given here assumes no changes in the reference engine system (for example change to the mini tank concept), no change in the reference method of startup (for example, tank pressure flow during chilldown instead of powered chill which is the presently assumed approach), and availability of computer time on the IBM 360, UNIVAC 1108 and Sigma 5 hybrid system.

2. INITIAL CONDITIONS FOR STARTUPS TO BE CONSIDERED
IN THE INITIAL CONTROL STUDY

The initial startup control design effort will be restricted to designing a control system which can start the engine up from a limited set of initial conditions. Depending on the engine's operating history prior to the command for startup initiation, there are numerous and very different sets of initial conditions each requiring differences in the startup sequence.

Once the initial effort treating this limited set of initial conditions is completed, variations in the initial conditions (variations in temperature distribution, H_2 distribution, initial power level, critical position uncertainty, and corrosion lifetime) will be investigated and the control system design extended to treat the general set of initial states.

Three somewhat diverse initial conditions will be treated in the initial design effort. These are: (1) Startup from ambient space soak conditions, (2) startup from an early point in the cooldown mode, and (3) startup from late in cooldown. Figure 3 shows the values of key parameters in each of these cases. The initial conditions for cases (2) and (3) were obtained from S-001 cooldown runs which assumed 10 min of full power operation and a 40 sec throttle hold.

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FIGURE 3INITIAL CONDITIONS FOR STARTUPS TO BE
CONSIDERED IN THE INITIAL CONTROL STUDY

1. STARTUP FROM AMBIENT SPACE SOAK CONDITIONS
 - . Engine System at Steady State
 - . Fission Power at Source (Approximately 3 mW)
 - . Decay Power Zero
 - . All System Components at 400°R
2. STARTUP FROM AN EARLY POINT DURING COOLDOWN MODE
 - . Engine System in a Cooldown Transient
 - . Fission Power Low (.3 MW)
 - . Decay Power High (8.55 MW)
 - . Core and Chamber Still Warm (1660°R)
 - . Reflector Well Below its Temperature Limit (500°R)
 - . Support Stem Liner Near its Temperature Limit (CRD)
 - . Pumps Relatively Cool (40°R)
3. STARTUP FROM LATE COOLDOWN
 - . Engine System in a Cooldown Transient
 - . Fission Power at Source (Approximately 3 mW)
 - . Decay Power Low (1.95 MW)
 - . Core and Chamber Down (920°R)
 - . Reflector Near its Temperature Limit (770°R)
 - . Support Stem Liner Down (CRD)
 - . Pumps Warm

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3. STARTUP ENGINE CONDITIONING (SEC) CONTROL

The following description is primarily of the SEC control logic being developed for NERVA. In order to establish the basis for this logic, however, it will be necessary to describe some of the requirements, assumptions, and interactions with other phases of engine control and/or the stage.

The basic requirements for SEC are contained in memo N8630:5126M, Design Requirements for Startup Control, which is enclosed as Attachment 1. To satisfy the direct requirements certain stage/engine functions/requirements must be assumed. Figure 4 shows a functional interface of SEC and stage. The first function shown in a "time to next start" signal from the stage shown going to a "cooldown/start control" block. This block assumes that if the start is to occur during the cooling cycle, the cycle will be modified by flowing through the pumps (PSOV's) and/or modifying the cycle to attain satisfactory start conditions.

The second function is a "time required for startup" sent from the SEC timing calculations, which provides to the stage the maximum time required for conditioning (estimate plus estimate tolerance). The time to start estimate is considered to be compared to required startup timing by the G&C system, with an "initiate startup" signal being transmitted to the engine control when the times become equal. This initiate startup signal is shown as the fourth function, where the engine conditioning will occur to bring the engine into a condition ready for the rise from low pump speed and low power to the operating line where control is transferred to the TBU control.

The third function is shown as an external selection of either power (S/N) or temperature (TMPS) control of the power rise to a sensible heating level (nuclear

*Assumes cooldown modified for startup by flow through PSOVs and/or cycle change for temperature distribution.

**May be active at startup initiation if start time not critical or set at required time.

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FIGURE 4

ENGINE CONDITIONING AND FLIGHT CONTROL RELATION

Enclosure (1)

- 8 -

or temperature autostart in the technology program). The external selection may or may not be a flight provision but is included for at least ground testing. In addition, the internal function of the control indicates either TMPS selected or a check made of decay power to neutron power ratio (DT/SN) to see if nuclear measurement is suitable for startup control. If DT/SN is too high TMPS is automatically selected.

When turbopump chill and engine thermal conditioning have been completed a flag (fifth function) is sent to G&C and hold conditions are maintained. When the flag has been transmitted the G&C can initiate the rise to TBU control and subsequent rise to full thrust per required timing (sixth function). For cases where the tolerance of the "time required for startup" is sufficient for thrust timing requirements, the signal may be activated at the same time as the "initiate startup" and the rise to TBU control will start at "conditioning complete."

Figure 5 is a simplified logic flow chart of the engine conditioning phase of startup (SEC). The purpose of this figure is to convey the primary functions required for SEC, with many secondary functions, malfunction provisions, calculations, stage/engine interaction and logic organization provisions being omitted. Most of the omissions will be covered later in the description of the actual "preliminary engine conditioning logic flow chart" but the discussion here of Figure 5 will serve to describe the SEC logic for those not interested in the greater detail and as an introduction for the following detail discussion.

The start engine conditioning signal from the stage, crew or ground test operator is received by Block 1 in Figure 5. It is assumed here that a time to start estimation has been sent to the stage/crew which includes allowance for the tolerance and that the receipt of the start command is when the desired

SIMPLIFIED ENGINE CONDITIONING LOGIC FLOW CHART

FIGURE 5

- 10 -

start time equals the estimated required time. In Block 1, estimated times for bootstrap conditioning (TBC), power rise to heating range (TPR), and temperature rise to a reference level suitable for power chill (TTR) are compared and if TBC is not greater than TPR plus TTR plus a preset time (T_1) a "no" answer results. A second interrogation is then made (Block 2) to see if TBC is less than TPR by more than a set time (K_1). If the answer to Block 2 is "no" then the TBC is equal to TPR plus TTR within a preset tolerance which insures that overcooling and/or over temperature is avoided and that minimum timing and propellant consumption are achieved. A "no" answer from both Blocks 1 and 2 results in initiating (Block 3) drum and SSCV position profiles and pump chill. The system continues waiting for power to reach a significant heating level (Block 4) by cycling back essentially through the same logic. It should be noted at this point that blocks stating "start....." are considered throughout this figure to imply "continue....." on passes through the logic following the first pass.

If TBC is greater than $TPR + TTR + K_1$ (Block 1), a check is made to see that the flow will not overcool the engine prior to achieving sensible heating (Block 5) and if overcooling will not occur, flow is started to chill the pump (Block 6). The flow is continued by cycling through the logic until Block 1 becomes "no" (Block 2 will automatically be "no") and Block 3 starts the drum/SSCV profiles, or until Block 7 starts the drums/SSCV profiles, the drum/SSCV profile is started by a "no" answer from Block 5, the time/temperature/power relation is such that a "yes" answer from Block 5 is attained prior to a "yes" from Block 4. Essentially the same sequence is followed if the initial answer to Block 5 is "no".

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If the initial answer to Block 1 is "no" and Block 2 is "yes" the time to get power is significantly greater than the time required for pump chill and the drum/SSCV profiles are started prior to initiating flow. (The SSCV opening with no flow is not of significance but fits in with the following events where flow is initiated). This sequence prevents overcooling and/or excessive flow at lower temperature (I_{sp}). The result is power increasing until Block 2 becomes "no" and flow is initiated by Block 3. The system then waits for Block 4 to become "yes" as in the previous cases.

When Block 4 has been satisfied, temperature control is initiated (Block 3) to bring the engine to the level of temperature required for power chill. A check is then made (Block 9) to see if the pump is adequately chilled to proceed with power chill. If the answer is "no" temperature control is maintained until the answer to Block 9 is "yes". When Block 9 is "yes" a check is made (Block 10) to see if the reflector/turbine-inlet and chamber conditions are satisfactory to maintain a bootstrap. If the answer to Block 10 is "no" the temperature level is modified (Block 11) to achieve the required conditions. The present logic is set up to continue flow in the event of a "no" answer to Block 10 for simplicity but analysis may show a significant gain by flow termination or modification for this case. When Blocks 9 and 10 are both "yes" the power chill is initiated (Block 12).

Power chill is initiated by opening the turbine block valves and programming the PDCVs in the closed direction (BCVs previously opened). At this time a bleed from the pump discharge back to the run tank is initiated (Block 13) which will be used during the power chill to prevent reaching a specified minimum flow over speed (Q/N) ratio. The system continues in temperature and open loop valve position control until turbopump speed reaches a preset value (Block 14).

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When speed has reached the set level (K_3), control of speed is initiated (Block 15) using the PDCVs. Speed and temperature control then continue until sufficient chilling has occurred to insure the proper thermal conditions for turbopump bearings and thrust balancers (Block 16) which has been labeled here "chill point #2".

When Block 16 is "yes" the engine conditioning is essentially complete and a flag (Block 17) is set indicating "ready for thrust buildup". The flag sets the SEC logic and is sent to the stage/crew. If the time of thrust buildup is not critical the signal (thrust buildup command) may already be present and the answer to Block 18 would be "yes". If the timing is critical the stage would supply the signal at the appropriate time and the answer to Block 18 would initially be "no". If Block 18 is "no", temperature control is continued and speed control modified by pressure is used (Block 19). When the TBU command is received, a rise to the engine operating line is initiated (Block 20).

During the rise to the operating line the recirculating flow to the run tank is shut off (Block 21) (may actually occur during TBU control pending analysis results).

When the system demands reach a point on the operating line (Block 22) the engine is in a condition to be turned over to the TBU controller (Block 23).

The detail logic flow chart of the SEC supervisory system is shown in Figures 6a through 6d, with the definition of symbols and list of equations in Figures 7a and 7b. This logic will be described here in terms of its expansion of detail and additional functions as compared to the simple logic previously described.

ENGINE CONDITIONING CONTROL LOGIC FLOW CHART

FIGURE 6a

- 14 -

ENGINE CONDITIONING CONTROL LOGIC FLOW CHART

FIGURE 6b

- 15 -

ENGINE CONDITIONING CONTROL LOGIC FLOW CHART

FIGURE 6c

ENGINE CONDITIONING CONTROL LOGIC FLOW CHART

FIGURE 6d

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FIGURE 7aDEFINITION OF SYMBOLS

tBC1 = Pump #1 Bootstrap Conditioning Time

tBC2 = Pump #2 Bootstrap Conditioning Time

tBC = Total Bootstrap Conditioning Time

tPR = Time Required to Raise Neutron Power to Positive Heat Rate
at Existing Conditions

tCO = Time of Measurement (During Coolant Off Period in Cooldown)

tCP = Time to Reach Critical Position

tTR = Time to Bring TC to TREF1

tH = Nominal Hold Time At or Near TREF1

tPC = Time Required for Power Chill

TREF1 = Nominal Hold Temperature for Power Chill Plus Tolerance Hold

TC = Measured Average Thrust Chamber Temperature

TPR = Temperature Measurement Calculation for Detecting Sensible Heat

TSA = Temperature Measurement Calculation Nuclear Average for Critical
Position Determination/Adjustment

TBA = Effective Thermal Bulk Average Temperature for Latent
Heat Evaluation

TRFL = Average Reflector Temperature (Weighted)

T1 = Minimum TBA Level for Flow Initiation

TSSC = Support System Temperature Calculation for Startup

TTP1 = Temperature in Pump(s) Required for Head Rise Req.,
Must be T3.

TTP2 = Pump(s) Temperature. Req. for Thermal Balance (Piston and Bearings)

T4 = Calc. TC Level to Support Power Chill Without Overchill of Reflector

TBU = Thrust Buildup

TMPS = Temperature Startup Control Mode

T3 = Minimum Temp. for Pump Readiness

Figure 7a (continued)

f1 = Constant Calculated to Insure Heat Extracted by Chiltdown Will not Reduce TBA Excessively Before Neutron Heat is Up

VProg = Programmed Position Profiles of Valves (Several Sets Depending on Failure Status)

VRef = Reference Positions for Valves Including Binary for Start of Engine Conditioning (Several Sets Depending on Failure Status)

THTC = Existing Critical Position Calculation

f2 = Constant to insure Pumps Both Chilled by Approximately the Same Time and/or Before T4 is Reached

N = Calculated/Measured Neutron Power

H = Total Power (Decay Heat Plus Neutron)

DT = Total Decay Heat Meas/Calc.

Dcalc = Calc. Decay Heat from Run History

QN = Flow/Pump Speed (Gal/Min/RPM)

PER = Reactor Period

FIGURE 7b

LIST OF EQUATIONS

1. $H = SN + DT$
2. $SN = \text{Calc/Meas Neutron Power (TBD)}$
3. $DT = \left(\frac{C_1 \Delta TBA}{\Delta t CO} - \frac{C_2}{SN} \right) W_1$
 $+ D_{calc} W_2 \quad (W_1, W_2 = \text{weighting factors})$
4. $tBC = \text{Greater of } tBC1 \text{ and } tBC2$
5. $tBC1 = C3 (TTP11 - T3) + (C4)H$
6. $tBC2 = C3 (TTP12 - T3) + (C4)H$
7. $TTP1 = f(\text{material/fluid temp. meas}) \text{ (TBD)}$
8. $TTP2 = f(\text{material temp. meas. and time}) \text{ (TBD)}$
9. $tPR = tCP + C5 \log SN$
10. $C5 = f(TBA) \text{ (TBD)}$
11. $TBA = f(\text{engine material temps.}) \text{ (TBD)}$
12. $tCP = (C6)THTC$
13. $THTC = f(\text{last hold and last start position}) + f(TSA) \text{ (TBD)}$ (see RN-S-0510, Vol. III, Book 2, Section VI, D. for typical "last start" relation)
14. $TSA = f(\text{core, stem and reflector temps}) \text{ (TBD)}$ (see RN-S-0510, Vol. I, Book 1, Section XII, B. as typical)
15. $f1 = C7 (tBC - C8)$
16. $tTR = (T4 - TBA)C9 - C10 \frac{\dot{}}{TBA}$
17. $T4 = f(TRFL, TTP2) \text{ (TBD)}$
18. $TRFL = f(\text{reflector mat. temp. and turbine-inlet/refl.-outlet gas temp.}) \text{ (TBD)}$
19. $tPC = f(TTP2, TTP1) \text{ (TBD)}$
20. $tH = f(\text{time to start tolerance, and } tPC) \text{ (TBD)}$
21. $TPR = f(\text{core temperature, cooling history, } H) \text{ (TBD)}$
22. $TSSC = f(\text{fluid and material temps.}) \text{ (TBD)}$
23. $D_{calc} = f(\text{power and run time}) \text{ (TBD)}$
24. $Q/N = \text{Meas. of Calc. Pump-Flow/Pump-Speed (TBD)}$
25. $PER = 1/\frac{d \log SN}{dt}$

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Blocks 1 through 13 provide the timing of pump chill, bringing power into the heating region, and raising of temperature to required power chill levels. These blocks also provide for the option of power or temperature control of the initial power rise (Blocks 6 through 10). As noted, these timing provisions insure that overcooling, overtemperature and inefficient chilldown conditions are avoided. At Block 14, a check is made to see if this is the first pass through this logic for a given startup. If it is the first pass (KFlag 3=0), Blocks 15 through 24 test for various malfunctions and set flags such that the program (VPROG) matrix of valve conditions and profiles and system gains are set to accommodate the existing malfunction conditions. On succeeding passes through the logic, for a given startup, these tests are bypassed and the sequence proceeds from Block 14 to Block 25.

If one TPA is out (Block 25) the PSOV is opened and the startup proceeds. If, however, both TPAs are operative they may be thermally unbalanced. If chilldown flow were initiated through both pumps with a thermal unbalance most of the flow (if not all due to check valves) would go through the colder pump significantly increasing chilldown time for the warmer pump. Blocks 26 through 28, therefore, provide a sequence which chills the warmer pump until nearly equal thermal conditions exist in the two pumps, then allowing both pumps to chill together. If the case of long chill time and short power/temperature rise exist, the logic recycles (circle C) until the times come into the required balance. For the case of longer power/temperature rise times (or equal to the required degree) drums/SSCV operation will have been started and the logic proceeds to Block 31.

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Blocks 31 through 42 detect sensible heating and provide control to insure that, during periods of reflector/SSCV flow, the support system is not overcooled or at too high a temperature and that the turbine inlet temperature at the initiation of power chill is between preset limits.

Block 43 is a test to see if bootstrap has been initiated (KFLAG4 not zero). If not, the system is tested (Block 44) to see if sufficient chill has occurred to allow powering the turbine ($TTP1 < T3$). The logic cycles (circle E) until the condition is met. Then a check is made (Block 45) to see that chamber temperature is high enough to sustain bootstrap and bootstrap is initiated (Block 47). Until turbopump speed builds up to a preset level (Block 48) the logic recycles (circle F).

When speed reaches the set level, speed control is initiated using the PDCV(s), PDCV(s) are maintained in a controllable range using BCV(s) (PDCVT), and Q/N of the pump(s) is maintained using control of a recirculating pump discharge flow to the tank (Block 49). During the bootstrap, engine initial conditions may result in PDCV(s) opening beyond a controllable range and blocks 53 and 54 are provided to force the PDCV(s) back into a controllable range. Speed and temperature control are then maintained by cycling back through the logic until power chill is complete (Block 55).

Conditions are then held until the "TBU command" has been received (Block 57). Then pressure control is attained and a rise to the operating line is initiated (actually, state variable control will vary gains instead of "closed PC loop"). During the rise to or shortly after reaching the operating line, the recirculating flow for Q/N control will go to zero and the control will be terminated.

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When the control demands have reached the engine operating line, control will be transferred to the TBU controller (Blocks 64 and 65).

Figure 8 shows the open loop demand programs for control valves and controlled variables in a nominal startup from ambient conditions. The demands are stored in terms of rates to minimize the amount of computer storage. Initial control valve positions are indicated and initial values for controlled variable demands are set equal to measured valves upon initiation of their respective control.

4. STARTUP DIGITAL CONTROL PROGRAM

A digital program has been written for direct digital control of the E-1 CAM startup model. The program written in Fortran for the Sigma 5 computer has a main program and one subroutine. The main program carries out the startup supervisory logic discussed previously while the subroutine performs the closed loop control calculations, control valve programming, and binary valve sequencing as selected by the main supervisory program.

Figure 9 shows a simplified block diagram of the computations performed in the program. Input data is first read into the main program. This data consists of the initial values for variables to be calculated (for use in the supervisory logic), program constants, flag constants, initial valve positions, valve programmer arrays, and feedback gain matrices. The input data is then printed out to insure a correct read-in. The main program is devoted to carrying out the startup supervisory logic discussed previously. In essence, the supervisory logic determines the status of the engine system from measurements and calculated variables which are functions of the measured variables. Based on what point in the engine conditioning phase the engine is in, the main supervisory program specifies appropriate binary valve sequencing, control valve programmer

FIGURE 9

BLOCK DIAGRAM OF STARTUP

DIGITAL CONTROL PROGRAM

MAIN:

SUBROUTINE:
(SUCNTR)

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demands, and the mode of closed loop control to be enacted by the control subroutine. Interrupts are made at various points throughout the logic to call the subroutine for on-line control calculations. Once the subroutine's control calculations are completed for the immediate time frame, return is made back to the point in the main program logic which was interrupted.

The startup control subroutine (SUCNTR) and main program have all their data in common storage so that information is automatically transferred from one program to the other. Measured variables from the engine model are converted from analog to digital form and read into the control subroutine. A set of calculated variables employed in the main program's supervisory logic are then computed as functions of these measured variables. (The equations to determine these calculated variables are presently being generated and will subsequently be added to the program.) Next, binary valve sequencing and control valve programmer demands are determined as specified by the supervisory logic. The closed loop control portion of the subroutine has four options: (1) power control, (2) weighted system temperature control, (3) chamber temperature control with speed and Q/N control upon bootstrap initiation, and (4) chamber temperature and chamber pressure control with Q/N control. The control subroutine carries out the option selected by the supervisory logic. Each closed loop control mode has a feedback gain matrix to multiply its respective state variables. Included as states are the integrals of the controlled variable errors. The closed loop control valve demands obtained are then added to the open loop valve programs to determine the total demands. After scaling, these control valve demands and binary valve demands are sent to the engine model for control.

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The determination of state variables and design of feedback gains for each control mode are yet to be performed. While this parallel design effort is in progress simplified controllers (proportional plus integral) will be employed in the program to carry out program debugging and to perform initial studies on the startup model.

The equations for determining the calculated variables used in the supervisory logic and the DAC and ADC line addresses are yet to be included in the program. Once these are added, the program will be ready to be run and debugged. A listing of the startup control program in its present state is given in Figures 10a through 10n.

5. STARTUP FROM AMBIENT CONDITIONS USING ANALOG CONTROLS

In order to investigate startup model characteristics and obtain startup controllability data, analog controllers were used to perform engine conditioning from ambient conditions. While the controllers and startup sequencing used were far from optimum, they were sufficient to perform an adequate startup.

Figures 11a through 11d show the SUM model response for an ambient startup. In this run, pump chilldown and nuclear startup are carried out simultaneously. The initial control valve positions are $\theta_{BCV} = 100\%$, $\theta_{PDCV} = 60\%$ and $\theta_{SSCV} = 0\%$ while the control drums are at 0° . The PSOV is opened and the drums are ramped to 104° at $12^\circ/\text{sec}$. Measured chamber temperature slowly decreases until an increase in power level causes heating. At the point where chamber temperature increases an additional 75°R , the drums are ramped in to 89° at $12^\circ/\text{sec}$. At this point, if the pumps are chilled below 320° ($T_{12} < 320^\circ$) the PDCV is ramped to 10% at $100\%/\text{sec}$. Once the PDCV is at 10%, bootstrap is initiated by opening the TDCV to 100% at $200\%/\text{sec}$.

,1,711011, 35638

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C
C
C
C*****
C***      SUPERVISOR FOR CONTROL OF E-1 CAM
C***      DURING STARTUP MODE
C*****
C
C
C
C*****
C***      LOGICAL VARIABLES USED
C*****
C
      LOGICAL KNSU,CONT
C
C*****
C***      CONSTANTS IN COMMON STORAGE
C*****
C
      COMMON TIMH,TREF1,T1,T3,F2,XK1,XK2,XK3,XK4
      COMMON XK5,XK6,XK7,XK8,C1,C2,C3,C4,C5,C6
      COMMON C7,C8,C9,C10,PDCVMX,W1,W2
C
C*****
C***      FLAG CONSTANTS IN COMMON STORAGE
C*****
C
      COMMON KNSU,CONT,KBCV,KD,KSSCV,KPDCV,KCNTRL,KTMPS
      COMMON KTBUC,KMAL,KMAL1,KMAL2,KMAL3,KMAL4
      COMMON KMAL11,KMAL12,KMAL21,KMAL22,KMAL31,KMAL32,KMAL41,KMAL42
      COMMON KFLAG1,KFLAG2,KFLAG3,KFLAG4,KFLAG5,KFLAG6,KFLAG7,KFLAG8
      COMMON KBOTSP,KPSUB1,KLSBCV
C
C*****
C***      DATA ARRAYS IN COMMON STORAGE
C*****
C
      COMMON PROG(20,4,19),VPROG(20,4),VREF(14)
      COMMON G1(4,5),G2(4,6),G3(4,7),G4(4,9)
C
C*****
C***      CALCULATED VARIABLES IN COMMON STORAGE
C*****
C
      COMMON TIMBC1,TIMBC2,TIMBC,TIMPR,TIMCP,TIMTR
      COMMON TIMPC,DELTCO
      COMMON TPR,TSA,TBA,DELTBA,TBALST,TRFL,TSSC,CLKLST,SNLST
      COMMON TTP1,TTP11,TTP12,TTP2,T4,THTC,TPRT
      COMMON F1,H,DT,DCALC,QN,PER,XN
      COMMON BCVD,DD,SSCVD,PDCVD
      COMMON UO(14),XO(8),XE(10),U(4),UD(14)
      COMMON TCD,PCD,TCDMOD
C
C*****
C***      MEASURED VARIABLES IN COMMON STORAGE

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FIGURE 10a

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C*****
C
COMMON CLOCK
COMMON TC,PC,SN,QR,XN1,XN2
C
C*****
C***      READ DATA
C*****
C
  READ(105,1000) TIMH,TREF1,T1,T3,F2,XK1,XK2,XK3,XK4,
1  XK5,XK6,XK7,XK8,C1,C2,C3,C4,C5,C6,C7,C8,C9,
2  C10,PDCVMX,W1,W2,TBALST,CLKLST,SNLST,TPRT
  READ(105,1001) KBCV,KD,KSSCV,KPDCV,KCNTRL,KTMPS,KTBU,
1  KTBUC,KMAL,KMAL1,KMAL2,KMAL3,KMAL4,KFLAG1,
2  KFLAG2,KFLAG3,KFLAG4,KFLAG5,KFLAG6,KFLAG7,KFLAG8,
3  KBOTSP,KPSUB1,KLSBCV,KMAL11,KMAL12,KMAL21,KMAL22,KMAL31,
4  KMAL32,KMAL41,KMAL42
  READ(105,1002) (((PROG(J,K,I),K=1,4),J=1,20),I=1,19)
  READ(105,1000) VREF
  READ(105,1003) G1
  READ(105,1003) G2
  READ(105,1003) G3
  READ(105,1003) G4
1000 FORMAT(F20.4)
1001 FORMAT(I4)
1002 FORMAT(4F20.4)
1003 FORMAT(4D18.8)
C
C*****
C***      WRITE DATA
C*****
C
  WRITE(108,1004)
  WRITE(108,1005)
  WRITE(108,1006) TIMH,TREF1,T1,T3,F2,XK1,XK2,XK3,XK4,
1  XK5,XK6,XK7,XK8,C1,C2,C3,C4,C5,C6,C7,C8,C9,
2  C10,PDCVMX,W1,W2,TBALST,CLKLST,SNLST,TPRT
  WRITE(108,1007)
  WRITE(108,1008) KBCV,KD,KSSCV,KPDCV,KCNTRL,KTMPS,KTBU,
1  KTBUC,KMAL,KMAL1,KMAL2,KMAL3,KMAL4,KFLAG1,
2  KFLAG2,KFLAG3,KFLAG4,KFLAG5,KFLAG6,KFLAG7,KFLAG8,
3  KBOTSP,KPSUB1,KLSBCV,KMAL11,KMAL12,KMAL21,KMAL22,KMAL31,
4  KMAL32,KMAL41,KMAL42
  WRITE(108,1009)
  WRITE(108,1010) (((PROG(J,K,I),K=1,4),J=1,20),I=1,19)
  WRITE(108,1011)
  WRITE(108,1012) VREF
  WRITE(108,1013)
  WRITE(108,1014) ((G1(I,J),J=1,5),I=1,4)
  WRITE(108,1015) ((G2(I,J),J=1,6),I=1,4)
  WRITE(108,1016) ((G3(I,J),J=1,7),I=1,4)
  WRITE(108,1017) ((G4(I,J),J=1,9),I=1,4)
1004 FORMAT(1H1)
1005 FORMAT(25H0VALUES FOR THE CONSTANTS)
1006 FORMAT(1H ,10X,8E10.3)
1007 FORMAT(38H0INITIAL VALUES FOR THE FLAG CONSTANTS)
1008 FORMAT(1H ,10X,8I10)
1009 FORMAT(29H0THE PROGRAMMER DATA ARRAY IS)
1010 FORMAT(1H0,20(10X,4E10.3))
1011 FORMAT(42H0THE INITIAL VALVE REFERENCE POSITIONS ARE)

```

FIGURE 10b


```

1012 FORMAT(1H ,10X,E10.3)
1013 FORMAT(22H0THE GAIN MATRICES ARE)
1014 FORMAT(1H ,5E13.6)
1015 FORMAT(1H ,6E13.6)
1016 FORMAT(1H ,7E13.6)
1017 FORMAT(1H ,9E13.6)

```

```

C
C*****
C***          STARTUP LOGIC
C*****
C
      CALL RSL(KNSU, )
      1 CALL SUCNTR
        IF(KNSU) GO TO 1
      10 IF(TIMBC-TIMPR-TIMTR-TIMH) 50,50,20
      20 IF(TBA-T1-XK2) 25,25,30
      25 IF(H-F1) 48,48,30
      30 IF(KFLAG3) 35,35,110
      35 KFLAG3=1
        IF(KMAL1) 40,40,38
      38 KMAL=KMAL+KMAL1
      40 IF(KMAL2) 80,80,45
      45 KMAL=KMAL+KMAL2
        IF(KMAL21.EQ.1) U0(9)=0.0
        IF(KMAL22.EQ.1) U0(10)=0.0
      80 IF(KMAL3) 90,90,85
      85 KMAL=KMAL+KMAL3
        IF(KMAL31.EQ.1) U0(5)=0.0
        IF(KMAL32.EQ.1) U0(6)=0.0
      90 IF(KMAL4) 100,100,95
      95 KMAL=KMAL+KMAL4
        IF(KMAL41.EQ.1) U0(7)=0.0
        IF(KMAL42.EQ.1) U0(8)=0.0
    100 IF(KMAL.EQ.0) I=1
        IF(KMAL.EQ.1) I=2
        IF(KMAL.EQ.10) I=3
        IF(KMAL.EQ.100) I=4
        IF(KMAL.EQ.1000) I=5
        IF(KMAL.EQ.11) I=6
        IF(KMAL.EQ.101) I=7
        IF(KMAL.EQ.1001) I=8
        IF(KMAL.EQ.110) I=9
        IF(KMAL.EQ.1010) I=10
        IF(KMAL.EQ.1100) I=11
        IF(KMAL.EQ.111) I=12
        IF(KMAL.EQ.1011) I=13
        IF(KMAL.EQ.1101) I=14
        IF(KMAL.EQ.1110) I=15
        IF(KMAL.EQ.1111) I=16
        DO 105 J=1,20
        DO 105 K=1,4
    105 VPROG(J,K)=PROG(J,K,I)
    110 IF(KMAL1) 112,112,120
    112 IF(TIMBC1-TIMBC2-F2) 114,114,113
    114 IF(TIMBC2-TIMBC1-F2) 120,120,115
    113 U0(11)=100.0
        GO TO 130
    115 U0(12)=100.0
        GO TO 130
    120 IF(KMAL11.EQ.0) U0(11)=100.0

```

FIGURE 10c

```

      IF(KMAL12.EQ.0) U0(12)=100.0
      KFLAG1=1
      GO TO 130
48  CALL SUCNTR
50  IF(U0(11).GT.0.0.OR.U0(12).GT.0.0) GO TO 55
      KCNTRL=0
      KD=1
      GO TO 60
55  KCNTRL=0
      KD=1
      KSSCV=1
60  IF(KTMPS) 65,65,70
65  IF((DT/SN)-XK7) 66,66,67
66  IF(SN-XK8) 70,70,68
67  KCNTRL=2
      GO TO 70
68  KCNTRL=1
70  IF(TIMBC-TIMPR+XK1) 8,8,20
      8 CALL SUCNTR
      GO TO 10
130 IF(KD.EQ.1.AND.KSSCV.EQ.1) GO TO 150
140 CALL SUCNTR
145 IF(THTC.GT.XK3) GO TO 140
      GO TO 10
150 DO 155 J=1,20
155 VPROG(J,3)=
      CALL SUCNTR
      IF(TPR.LT.TPRT) TPRT=TPR
      IF(KFLAG1) 110,110,158
158 IF(TPR-TPRT-XK4) 150,150,159
159 KCNTRL=3
160 IF(TRFL-XK5) 165,165,170
165 TCDMOD=
168 CALL SUCNTR
      GO TO 160
170 IF(TRFL-XK6) 176,174,174
174 TCDMOD=
175 CALL SUCNTR
      GO TO 170
176 DO 1760 J=1,20
1760 VPROG(J,3)=(1.0+F(TSSC))*VPROG(J,3)
      IF(KFLAG4) 177,177,180
177 CONTINUE
      IF(U0(11).GT.0.0.AND.TTP11.GE.T3) GO TO 150
      IF(U0(12).GT.0.0.AND.TTP12.GE.T3) GO TO 150
178 IF(TC.LE.T4) GO TO 150
      KBCV=1
      KPDCV=1
      U0(13)=100.0
      U0(14)=100.0
      KFLAG4=1
185 IF(U0(11).GT.0.0.AND.XN1.LE.XK7) GO TO 186
      IF(U0(12).GT.0.0.AND.XN2.LE.XK7) GO TO 186
      KBOTSP=1.0
      KFLAG2=1.0
      GO TO 190
180 IF(KFLAG2) 185,185,190
186 IF(PDCVD-PDCVMX) 200,188,188
188 KLSBCV=1
200 CALL SUCNTR

```

FIGURE 10d

```

GO TO 160
190 IF(TTP2.GE.XK8) GO TO 200
    KTBU=1
210 CALL SUCNTR
    IF(KTBUC.NE.1) GO TO 210
    KCNTRL=4

220 CALL SUCNTR

```

```

230 CALL SUCNTR
    IF(ABS(TCD-13.64*PCD-568.).GT..01) GO TO 230

```

```

C
C*****
C***          INITIAL CONDITIONS AVAILABLE TO  TBU CONTROL
C***          PROGRAM THROUGH COMMON STORAGE
C*****
C
    KTBU=2
    CALL RSL(CONT, )
    IF(CONT) GO TO 230
    STOP
    END

```

```

C*****

```

```

C
C*****
C***          STARTUP CONTROL SUBROUTINE, SUCNTR
C***          WHICH ENACTS THE CONTROL MODE SELECTED
C***          BY THE SUPERVISORY LOGIC
C*****
    SUBROUTINE SUCNTR

```

```

C
C*****
C***          LOGICAL VARIABLES USED
C*****
    LOGICAL KNSU,CONT

```

```

C
C*****
C***          CONSTANTS IN COMMON STORAGE
C*****
    COMMON TIMH,TREF1,T1,T3,F2,XK1,XK2,XK3,XK4
    COMMON XK5,XK6,XK7,XK8,C1,C2,C3,C4,C5,C6
    COMMON C7,C8,C9,C10,PDCVMX,W1,W2

```

```

C
C*****
C***          FLAG CONSTANTS IN COMMON STORAGE
C*****
    COMMON KNSU,CONT,KBCV,KD,KSSCV,KPDCV,KCNTRL,KTMPS
    COMMON KTBU,KTBUC,KMAL,KMAL1,KMAL2,KMAL3,KMAL4
    COMMON KMAL11,KMAL12,KMAL21,KMAL22,KMAL31,KMAL32,KMAL41,KMAL42
    COMMON KFLAG1,KFLAG2,KFLAG3,KFLAG4,KFLAG5,KFLAG6,KFLAG7,KFLAG8
    COMMON KBOTSP,KPSUB1,KLSBCV

```

```

C

```

FIGURE 10e


```

C*****
C***      DATA ARRAYS IN COMMON STORAGE
C*****
C
COMMON PROG(20,4,19),VPROG(20,4),VREF(14)
COMMON G1(4,5),G2(4,6),G3(4,7),G4(4,9)
C
C*****
C***      CALCULATED VARIABLES IN COMMON STORAGE
C*****
C
COMMON TIMBC1,TIMBC2,TIMBC,TIMPR,TIMCP,TIMTR
COMMON TIMPC,DELTCO
COMMON TPR,TSA,TBA,DELTBA,TBALST,TRFL,TSSC,CLKLST,SNLST
COMMON TTP1,TTP11,TTP12,TTP2,T4,THTC,TPRT
COMMON F1,H,DT,DCALC,QN,PER,XN
COMMON BCVD,DD,SSCVD,PDCVD
COMMON UO(14),XO(8),XE(10),U(4),UD(14)
COMMON TCD,PCD,TCDMOD
C
C*****
C***      MEASURED VARIALBES IN COMMON STORAGE
C*****
C
COMMON CLOCK
COMMON TC,PC,SN,QR,XN1,XN2
C
C*****
C***      READ MEASURED VARIABLES FROM
C***      ADC LINES AND CLOCK TIME FROM E5
C*****
C
S      LI,8      X'F8  '
S      LI,10     TC
S      CAL3,5    $
S      LI,8      X'F8  '
S      LI,10     PC
S      CAL3,5    $
S      LI,8      X'F8  '
S      LI,10     SN
S      CAL3,5    $
S      LI,8      X'F8  '
S      LI,10     QR
S      CAL3,5    $
S      LI,8      X'F8  '
S      LI,10     XN1
S      CAL3,5    $
S      LI,8      X'F8  '
S      LI,10     XN2
S      CAL3,5    $
CALL TIME(ITIME)
CLOCK= ITIME
CLOCK= CLOCK/1000.0
C
C*****
C***      UNSCALE THE MEASURED VARIABLES
C***      TO ENGINEERING UNITS
C*****
C
TC=TC*

```

FIGURE 10f

```

PC=PC*
SN=SN*
QR=QR*
XN1=XN1*
XN2=XN2*

```

C

```

C*****

```

```

C***      EQUATIONS TO DETERMINE

```

```

C***      CALCULATED VARIABLES

```

```

C*****

```

C

C

```

TTP11=
TTP12=
TTP1=
TTP2=
TBA=
TSA=
TRFL=
TIMPC=
TIMH=
TSSC=
DCALC=
QN=
C5=
THTC=
T4=
TIMCP=C6*THTC
TIMPR=TIMCP + C5 * ALOG (SN)
DELTBA= TBA-TBALST
DELTCO= CLOCK-CLKLST
FRAC= DELTBA/DELTCO
IF(                                     )  FRAC=0.0
DT=(C1*FRAC-C2/SN)*W1+DCALC*W2
H= SN+DT
TIMBC1= C3*(TTP11-T3) + C4 * H
TIMBC2 = C3*(TTP12-T3) + C4 * H
TIMBC = TIMBC1
IF ( TIMBC2 .GT. TIMBC1) TIMBC=TIMBC2
F1 = C7 * (TIMBC -C8)
TIMTR= (T4-TBA)*C9 -C10 * FRAC
TPR=
PER=1.0/((ALOG(SN)-ALOG(SNLST))/DELTCO)
IF(KPSUB1.EQ.0) PER=1000.
IF(KMAL11.EQ.0.AND.KMAL12.EQ.0) XN=(XN1+XN2)/2.0
IF(KMAL11.EQ.0.AND.KMAL12.EQ.1) XN=XN1
IF(KMAL11.EQ.1.AND.KMAL12.EQ.0) XN=XN2

```

C

```

C*****

```

```

C***      SET BINARY VALVES AND INITIALIZE CONTROL

```

```

C***      VALVES BASED ON VREF FOR THE FIRST PASS

```

```

C***      THROUGH THIS SUBROUTINE . ZERO PROGRAMMER

```

```

C***      CLOCKS, ZERO DIGITAL INTEGRATORS, AND SPECIFY

```

```

C***      PROGRAMMER TOTAL TIMES ON INITIAL

```

```

C***      PASS.

```

```

C*****

```

C

```

IF(KPSUB1.EQ.1) GO TO 10
DO 5 I=1,14
UO(I)=VREF(I)

```

FIGURE 10g

5. CONTINUE

TIME1=

TIME2=

TIME3=

TIME4=

TIMC1=

TIMC2=

TIMC3=

TIMC4=

TIMC5=

TIMC6=

TIMC7=

CLKLST=CLOCK

CLOCK1=0.

CLOCK2=0.

CLOCK3=0.

CLOCK4=0.

CLCK1=0.

CLCK2=0.

CLCK3=0.

CLCK4=0.

CLCK5=0.

CLCK6=0.

CLCK7=0.

XE(3)=0.0

XE(5)=0.

XE(6)=0.

XE(7)=0.

XE(8)=0.

XE(9)=0.

KPSUB1=1

10 CONTINUE

C

C

C*****

C*** IF ANY CONTROL VALVES ARE TO BE

C*** PROGRAMMED REPLACE THEIR VREF DEMAND

C*** VALUES BY VPROG DEMANDS

C*****

C

IF(KBCV .EQ. 0) GO TO 20

CLOCK1=CLOCK1 + (CLOCK-CLKLST)

IT1=(CLOCK1/(TIME1/19.))+1.0

IF(IT1.GE.20) IT1=20

U0(1)=U0(1)+VPROG(IT1,1)*(CLOCK-CLKLST)

20 IF(KD. EQ. 0) GO TO 30

CLOCK2=CLOCK2+(CLOCK-CLKLST)

IT2=(CLOCK2/(TIME2/19.))+1.0

IF(IT2.GE.20) IT2=20

U0(2)=U0(2)+VPROG(IT2,2)*(CLOCK-CLKLST)

30 IF(KSSCV .EQ. 0) GO TO 40

CLOCK3=CLOCK3+(CLOCK-CLKLST)

IT3=(CLOCK3/(TIME3/19.))+1.0

IF(IT3.GE.20) IT3=20

U0(3)=U0(3)+VPROG(IT3,3)*(CLOCK-CLKLST)

40 IF(KPDCV .EQ. 0) GO TO 50

CLOCK4=CLOCK4+(CLOCK-CLKLST)

IT4=(CLOCK4/(TIME4/19.))+1.0

IF(IT4.GE.20) IT4=20

U0(4)=U0(4)+VPROG(IT4,4)*(CLOCK-CLKLST)

FIGURE 10h

50 CONTINUE

```

C
C*****
C***      SELECT CONTROL MODE BASED ON
C***      VALUE OF KCNTRL
C*****
C
C      GO TO (100,200,300,400),KCNTRL
C
C
C
C*****
C***      OPEN LOOP CONTROL, KCNTRL=0
C***      VALVES EITHER SET ACCORDING TO VREF OR
C***      PROGRAMMED ACCORDING TO VPROG, IF ACTUATOR
C***      PROGRAMMER FLAGS ARE SET TO 1.
C*****
C
C
C      BCVD=U0(1)
C      DD=U0(2)
C      SSCVD=U0(3)
C      PDCVD=U0(4)
C      GO TO 500
C
C*****
C***      CLOSED LOOP CONTROL OF POWER, KCNTRL=1
C***      VALVES EITHER SET ACCORDING TO VREF OR
C***      PROGRAMMED ACCORDING TO VPROG, IF ACTUATOR
C***      PROGRAMMER FLAGS ARE SET TO 1.
C*****
C
100 CLCK4=CLCK4+(CLOCK-CLKLST)
   ITC1=(CLCK1/(TIMC1/19.0))+1.0
   ITC2=(CLCK2/(TIMC2/19.0))+1.0
   ITC3=(CLCK3/(TIMC3/19.0))+1.0
   ITC4=(CLCK4/(TIMC4/19.0))+1.0
   ITC5=(CLCK5/(TIMC5/19.0))+1.0
   ITC6=(CLCK6/(TIMC6/19.0))+1.0
   ITC7=(CLCK7/(TIMC7/19.0))+1.0
   IF(ITC1.GE.20) ITC1=20
   IF(ITC2.GE.20) ITC2=20
   IF(ITC3.GE.20) ITC3=20
   IF(ITC4.GE.20) ITC4=20
   IF(ITC5.GE.20) ITC5=20
   IF(ITC6.GE.20) ITC6=20
   IF(ITC7.GE.20) ITC7=20
   IF(KFLAG5.EQ.1) GO TO 104
   KFLAG5=1
   X0(1)=0.0
   X0(2)=0.0
   X0(3)=0.0
   X0(4)=SN
104 CONTINUE
   X0(1)=X0(1)+PROG(ITC1,1,17)*(CLOCK-CLKLST)
   X0(2)=X0(2)+PROG(ITC2,2,17)*(CLOCK-CLKLST)
   X0(3)=X0(3)+PROG(ITC3,3,17)*(CLOCK-CLKLST)
   X0(4)=X0(4)+PROG(ITC4,4,17)*(CLOCK-CLKLST)
   X0(5)=X0(5)+PROG(ITC5,1,18)*(CLOCK-CLKLST)
   X0(6)=X0(6)+PROG(ITC6,2,18)*(CLOCK-CLKLST)

```

FIGURE 101

- 36 -

```

X0(7)=X0(7)+PROG(ITC7,3,18)*(CLOCK-CLKLST)
XE(1)=X0(1) -X0(1)
XE(2)=X0(2) -X0(2)
XE(3)=X0(3) -X0(3)
XE(4)=SN-X0(4)
XE(5)=XE(5)+XE(4)*(CLOCK-CLKLST)
DO 110 I=1,4
TEMP=0.0
DO 110 J=1,5
TEMP=TEMP+G1(I,J)*XE(J)
110 U(I)=TEMP
BCVD=U0(1)-U(1)
DD=U0(2)-U(2)
SSCVD=U0(3)-U(3)
PDCVD=U0(4)-U(4)
GO TO 500

```

C

```

C***      CLOSED LOOP CONTROL OF WEIGHTED SYSTEM
C***      TEMPERATURES, KCNTRL=2
C***      VALVES EITHER SET ACCORDING TO VREF OR
C***      PROGRAMMED ACCORDING TO VPROG, IF ACTUATOR
C***      PROGRAMMER FLAGS ARE SET TO 1.

```

C

```

200 CLCK4=CLCK4+(CLOCK-CLKLST)
CLCK5=CLCK5+(CLOCK-CLKLST)
ITC1=(CLCK1/(TIMC1/19.0))+1.0
ITC2=(CLCK2/(TIMC2/19.0))+1.0
ITC3=(CLCK3/(TIMC3/19.0))+1.0
ITC4=(CLCK4/(TIMC4/19.0))+1.0
ITC5=(CLCK5/(TIMC5/19.0))+1.0
ITC6=(CLCK6/(TIMC6/19.0))+1.0
ITC7=(CLCK7/(TIMC7/19.0))+1.0
IF(ITC1.GE.20) ITC1=20
IF(ITC2.GE.20) ITC2=20
IF(ITC3.GE.20) ITC3=20
IF(ITC4.GE.20) ITC4=20
IF(ITC5.GE.20) ITC5=20
IF(ITC6.GE.20) ITC6=20
IF(ITC7.GE.20) ITC7=20
IF(KFLAG6.EQ.1) GO TO 204
KFLAG6=1
X0(1)=0.0
X0(2)=0.0
X0(3)=0.0
X0(4)=SN
X0(5)=TPR
204 CONTINUE
X0(1)=X0(1)+PROG(ITC1,1,17)*(CLOCK-CLKLST)
X0(2)=X0(2)+PROG(ITC2,2,17)*(CLOCK-CLKLST)
X0(3)=X0(3)+PROG(ITC3,3,17)*(CLOCK-CLKLST)
X0(4)=X0(4)+PROG(ITC4,4,17)*(CLOCK-CLKLST)
X0(5)=X0(5)+PROG(ITC5,1,18)*(CLOCK-CLKLST)
X0(6)=X0(6)+PROG(ITC6,2,18)*(CLOCK-CLKLST)
X0(7)=X0(7)+PROG(ITC7,3,18)*(CLOCK-CLKLST)
XE(1)=X0(1) -X0(1)
XE(2)=X0(2) -X0(2)
XE(3)=X0(3) -X0(3)
XE(4)=SN-X0(4)

```

FIGURE 10j

```

    XE(5)=TPR-XO(5)
    XE(6)=XE(6)+XE(5)*(CLOCK-CLKLST)
    DO 210 I=1,4
    TEMP=0.0
    DO 210 J=1,9
    TEMP=TEMP+G2(I,J)*XE(J)
210 U(I)=TEMP
    BCVD=U0(1)-U(1)
    DD=U0(2)-U(2)
    SSCVD=U0(3)-U(3)
    PDCVD=U0(4)-U(4)
    GO TO 500

C
C*****
C***      CLOSED LOOP CONTROL OF CHAMBER TEMPERATURE,
C***      (AND SPEED CONTROL UPON BOOTSTRAP INITIATION, KBOTSP=1)
C***      KCNTRL=3
C***      VALVES EITHER SET ACCORDING TO VREF OR
C***      PROGRAMMED ACCORDING TO VPROG, IF ACTUATOR
C***      PROGRAMMER FLAGS ARE SET TO 1.
C*****
C
300 CLCK4=CLCK4+(CLOCK-CLKLST)
    CLCK5=CLCK5+(CLOCK-CLKLST)
    CLCK6=CLCK6+(CLOCK-CLKLST)
    IF(KBOTSP.EQ.1) CLCK2=CLCK2+(CLOCK-CLKLST)
    ITC1=(CLCK1/(TIMC1/19.0))+1.0
    ITC2=(CLCK2/(TIMC2/19.0))+1.0
    ITC3=(CLCK3/(TIMC3/19.0))+1.0
    ITC4=(CLCK4/(TIMC4/19.0))+1.0
    ITC5=(CLCK5/(TIMC5/19.0))+1.0
    ITC6=(CLCK6/(TIMC6/19.0))+1.0
    ITC7=(CLCK7/(TIMC7/19.0))+1.0
    IF(ITC1.GE.20) ITC1=20
    IF(ITC2.GE.20) ITC2=20
    IF(ITC3.GE.20) ITC3=20
    IF(ITC4.GE.20) ITC4=20
    IF(ITC5.GE.20) ITC5=20
    IF(ITC6.GE.20) ITC6=20
    IF(ITC7.GE.20) ITC7=20
    IF(KFLAG7.EQ.1) GO TO 304
    KFLAG7=1
    XO(1)=0.0
    XO(2)=XN
    XO(3)=0.0
    XO(4)=SN
    XO(5)=TPR
    XO(6)=TC
304 CONTINUE
    XO(1)=XO(1)+PROG(ITC1,1,17)*(CLOCK-CLKLST)
    XO(2)=XO(2)+PROG(ITC2,2,17)*(CLOCK-CLKLST)
    XO(3)=XO(3)+PROG(ITC3,3,17)*(CLOCK-CLKLST)
    XO(4)=XO(4)+PROG(ITC4,4,17)*(CLOCK-CLKLST)
    XO(5)=XO(5)+PROG(ITC5,1,18)*(CLOCK-CLKLST)
    XO(6)=XO(6)+PROG(ITC6,2,18)*(CLOCK-CLKLST)
    XO(7)=XO(7)+PROG(ITC7,3,18)*(CLOCK-CLKLST)
    XO(6)=XO(6)+TCDMOD
    XE(1)=XO(1) -XO(1)
    XE(2)=XN-XO(2)
    XE(3)=XE(3)+XE(2)*(CLOCK-CLKLST)

```

FIGURE 10k


```

IF(KBOTSP.EQ.0) XE(2)=0.0
IF(KBOTSP.EQ.0) XE(3)=0.0
IF(KBOTSP.EQ.0) X0(2)=XN
XE(4)=SN-X0(4)
XE(5)=TPR-X0(5)
XE(6)=TC-X0(6)
XE(7)=XE(7)+XE(6)*(CLOCK-CLKLST)
DO 310 I=1,4
TEMP=0.0
DO 310 J=1,9
TEMP=TEMP+G3(I,J)*XE(J)
310 U(I)=TEMP
BCVD=U0(1)-U(1)
DD=U0(2)-U(2)
SSCVD=U0(3)-U(3)
PDCVD=U0(4)-U(4)
IF(KLSBCV.EQ.1.AND.KBOTSP.EQ.0)U0(1)=U0(1)-1.0*(CLOCK-CLKLST)
IF(KBOTSP.EQ.1.AND.PDCVD.GT.60.0)U0(1)=U0(1)-1.0*(CLOCK-CLKLST)
IF(KBOTSP.EQ.1.AND.PDCVD.LT.30.0)U0(1)=U0(1)+1.0*(CLOCK-CLKLST)
GO TO 500

```

C

```

C*****
C***      CLOSED LOOP CONTROL OF CHAMBER TEMPERATURE AND
C***      CHAMBER PRESSURE, KCNTRL=4
C***      VALVES ARE PROGRAMMED ACCORDING TO VPROG,
C***      SINCE ALL ACTUATOR PROGRAMMER FLAGS SHOULD
C***      BE SET TO 1 AT THIS STAGE.
C*****

```

C

```

400 CLCK4=CLCK4+(CLOCK-CLKLST)
CLCK5=CLCK5+(CLOCK-CLKLST)
CLCK6=CLCK6+(CLOCK-CLKLST)
CLCK2=CLCK2+(CLOCK-CLKLST)
CLCK7=CLCK7+(CLOCK-CLKLST)
ITC1=(CLCK1/(TIMC1/19.0))+1.0
ITC2=(CLCK2/(TIMC2/19.0))+1.0
ITC3=(CLCK3/(TIMC3/19.0))+1.0
ITC4=(CLCK4/(TIMC4/19.0))+1.0
ITC5=(CLCK5/(TIMC5/19.0))+1.0
ITC6=(CLCK6/(TIMC6/19.0))+1.0
ITC7=(CLCK7/(TIMC7/19.0))+1.0
IF(ITC1.GE.20) ITC1=20
IF(ITC2.GE.20) ITC2=20
IF(ITC3.GE.20) ITC3=20
IF(ITC4.GE.20) ITC4=20
IF(ITC5.GE.20) ITC5=20
IF(ITC6.GE.20) ITC6=20
IF(ITC7.GE.20) ITC7=20
IF(KFLAG8.EQ.1) GO TO 404
KFLAG8=1
X0(1)=0.0
X0(2)=XN
X0(3)=0.0
X0(4)=SN
X0(5)=TPR
X0(6)=TC
X0(7)=PC
TRATE=100.+50.0*(1500.-TC)/500.
IF(TC.LE.1000.) TRATE=150.
IF(TC.GE.1500.) TRATE=100.

```

```

PRATE=.02*(TC-1000.)+11.
404 CONTINUE
X0(1)=X0(1)+PROG(ITC1,1,17)*(CLOCK-CLKLST)
X0(2)=X0(2)+PROG(ITC2,2,17)*(CLOCK-CLKLST)
X0(3)=X0(3)+PROG(ITC3,3,17)*(CLOCK-CLKLST)
X0(4)=X0(4)+PROG(ITC4,4,17)*(CLOCK-CLKLST)
X0(5)=X0(5)+PROG(ITC5,1,18)*(CLOCK-CLKLST)
X0(6)=X0(6)+TRATE*(CLOCK-CLKLST)
X0(7)=X0(7)+PRATE*(CLOCK-CLKLST)
XE(1)=X0(1) -X0(1)
XE(2)=X0(2) -X0(2)
XE(3)=X0(3) -X0(3)
XE(4)=SN-X0(4)
XE(5)=TPR-X0(5)
XE(6)=TC-X0(6)
XE(7)=PC-X0(7)
XE(8)=XE(8)+XE(6)*(CLOCK-CLKLST)
XE(9)=XE(9)+XE(7)*(CLOCK-CLKLST)
TCD=X0(6)
PCD=X0(7)
DO 410 I=1,4
TEMP=0.0
DO 410 J=1,10
TEMP=TEMP+G4(I,J)*XE(J)
410 U(I)=TEMP
BCVD=U0(1)-U(1)
DD=U0(2)-U(2)
SSCVD=U0(3)-U(3)
PDCVD=U0(4)-U(4)
IF(KLSBCV.EQ.1.AND.KBOTSP.EQ.0)U0(1)=U0(1)-1.*(CLOCK-CLKLST)
IF(KBOTSP.EQ.1.AND.PDCVD.GT.60.0)U0(1)=U0(1)-1.0*(CLOCK-CLKLST)
IF(KBOTSP.EQ.1.AND.PDCVD.LT.30.0)U0(1)=U0(1)+1.0*(CLOCK-CLKLST)
500 CONTINUE
IF(BCVD.GE.100.)BCVD=99.999
IF(DD.GE.180.)DD=180.
IF(SSCVD.GE.100.)SSCVD=99.999
IF(PDCVD.GE.100.)PDCVD=99.999
UD(1)=      *BCVD
UD(2)=      *DD
UD(3)=      *SSCVD
UD(4)=      *PDCVD
UD(5)=U0(5)
UD(6)=U0(6)
UD(7)=U0(7)
UD(8)=U0(8)
UD(9)=U0(9)
UD(10)=U0(10)
UD(11)=U0(11)
UD(12)=U0(12)
UD(13)=U0(13)
UD(14)=U0(14)

```

C

C*****

C*** WRITE CONTROL ACTUATOR AND BINARY VALVE

C*** DEMANDS ON DAC LINES

C*** AND CONTROL LINES

C*****

S LI,8 X'1F8 '

S LW,10 UD

S CAL3,5 \$

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```

S      LI,8      X'1F8  '
S      LW,10     UD+1
S      CAL3,5    $
S      LI,8      X'1F8  '
S      LW,10     UD+2
S      CAL3,5    $
S      LI,8      X'1F8  '
S      LW,10     UD+3
S      CAL3,5    $

IF(UD(5).GT.99.0)CALL WCL(1, )
IF(UD(5).LT.1.0)CALL WCL(2, )
IF(UD(6).GT.99.0)CALL WCL(1, )
IF(UD(6).LT.1.0)CALL WCL(2, )
IF(UD(7).GT.99.0)CALL WCL(1, )
IF(UD(7).LT.1.0)CALL WCL(2, )
IF(UD(8).GT.99.0)CALL WCL(1, )
IF(UD(8).LT.1.0)CALL WCL(2, )
IF(UD(9).GT.99.0)CALL WCL(1, )
IF(UD(9).LT.1.0)CALL WCL(2, )
IF(UD(10).GT.99.0)CALL WCL(1, )
IF(UD(10).LT.1.0)CALL WCL(2, )
IF(UD(11).GT.99.0)CALL WCL(1, )
IF(UD(11).LT.1.0)CALL WCL(2, )
IF(UD(12).GT.99.0)CALL WCL(1, )
IF(UD(12).LT.1.0)CALL WCL(2, )
IF(UD(13).GT.99.0)CALL WCL(1, )
IF(UD(13).LT.1.0)CALL WCL(2, )
IF(UD(14).GT.99.0)CALL WCL(1, )
IF(UD(14).LT.1.0)CALL WCL(2, )
CLKLST=CLOCK
TBALST=TBA
SNLST=SN
RETURN
END
C*****
C*****

```

FIGURE 11a

FIGURE 11b

FIGURE 11c

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FIGURE 11d

When turbine speed reaches 7500 RPM the PDCV is used for closed loop control of speed using the controller transfer function,

$$\frac{\theta_{\text{PDCV}_D}}{N_{\epsilon}} = \frac{.0254 (2.57S + 1)}{S} .$$

The speed demand is ramped to 9000 RPM at 1500 RPM/sec. Simultaneously the BCV is ramped down to 80% at .5%/sec.

The drums are then put into chamber temprature control using the controller transfer function.

$$\frac{\theta_{D_D}}{T_{C_{\epsilon}}} = \frac{.08 (1.59S + 1) (S + 1)}{S (.1 S + 1)^2} .$$

Chamber temperature demand is ramped to 1400°R at 22.5°R/sec.

When chamber pressure reaches 50 psia, closed loop pressure control is initiated using the PDCV. The pressure controller transfer function is,

$$\frac{\theta_{\text{PDCV}_D}}{P_{C_{\epsilon}}} = \frac{.8 (.4 S + 1) (.25 S + 1)}{S (.159 S + 1) (.04 S + 1)} .$$

As can be seen, the flow to speed ratio decreases below the stall limit of .1 to a value of .05 during bootstrap. Since in the present startup model stall characteristics are not sufficiently accurate, pump stall did not occur. However, to prevent violating this $Q/N > .1$ stall constraint, a recirculation of flow back to the tank is to be incorporated using the coolant supply line.

The transient response indicated here is generally unsatisfactory because the controllers used were preliminary controllers chosen for stable though not necessarily good transient performance. The poor performance shows especially in the power and temperature responses during closed loop chamber temperature control. However, adequate controllability was demonstrated for this startup sequence.

STARTUP (ENGINE CONDITIONING PHASE)
REQUIREMENTS

by

F. L. Openshaw

24 September 1971

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1.0 INTRODUCTION

The startup controls effort in CY 71 and CY 72 has three objectives which will be taken up one at a time as the effort matures. They are:

First

To produce an operating system for a nominal startup which, when implemented on the E5, will control the hybrid startup model thus facilitating further simulation studies.

Second

To develop a general purpose startup controller which will interface with controllers for other operational modes, and will be sufficiently mature to permit derivation of requirements for the control computer, for control measurements, and for actuator performance.

Third

To provide data, for inclusion in the S-102, which demonstrates satisfaction of all design requirements.

Startup requirements from various sources are compiled herein to provide a working document on which a startup control design can be based. Specifically, this document is oriented to setting forth the requirements oriented to the "engine conditioning" phase of the startup operation. The requirements include those which directly apply to startup and those which are derived from either general requirements or requirements for other phases of operation with which startup must be compatible. The requirements generally fall into categories of "mission or system operational requirements", or "requirements due to the reference engine design". In this document "mission/operational requirements" are listed and "requirements due to the reference engine design" which are encountered in

meeting the mission/operational requirement are listed as a subset or secondary requirement.

Many of the secondary requirements cannot be specified quantitatively at this time but are included in this document as: potential problems, design considerations, general statements, etc. Many of these will become quantitative requirements as design solutions are generated. The purpose here is to insure that the area is not overlooked in the design process.

2.0 STARTUP (NORMAL MODE)

Startup consists of engine conditioning (temperature conditioning, nuclear startup, and bootstrap) and thrust buildup. Startup is initiated upon receipt of a command signal to initiate propellant flow or nuclear startup and is completed when rated performance has been achieved within the specified controllability limits. The engine shall be capable of accomplishing temperature conditioning and nuclear startup simultaneously or sequentially depending on prior operating history. The engine shall be capable of meeting the following requirements during normal startup operations (CP-90290C, 3.1.1.1.5.1.2).

2.1 ENGINE CONDITIONING

Engine conditioning shall consist of that portion of startup to the inception of thrust buildup, namely temperature conditioning, nuclear startup and bootstrap.

2.1.1 CP-90290 Requirements

The engine shall be capable of entering the engine prestart phase for restart at any time after completing the shutdown phase of a previous operating cycle (CP-90290C, 3.1.1.1.6). (Included here since restart is the general case of startup and requirements apply.)

The engine shall be capable of being temperature conditioned and bootstrapped up to the initiation of thrust buildup within 3 hours (tbv). For burns following coast periods less than 3 hours, engine conditioning shall not exceed 1 hours (tbv). The propellant consumption during this time shall be less than 380 lbs (tbv). The total time required for these functions shall be predictable within ± 1 second (tbv). A hold period may be utilized to meet this time requirement for engine conditioning. The propellant consumption shall be predictable within ± 40 lb (tbv) (CP-90290C, 3.1.1.1.5.1.2.1).

Temperature Conditioning - Temperature conditioning is initiated at engine startup and consists of non-nuclear component and reactor thermal conditioning. These operations may be conducted separately or simultaneously depending on engine thermal conditions at startup (CP-90290C, 3.1.1.1.5.1.2.1.1).

Nuclear Startup - Nuclear startup may occur prior to or simultaneously with temperature conditioning. During nuclear startup reactor criticality shall be achieved (CP-90290 3.1.1.1.5.1.2.1.2).

Bootstrap - Bootstrap startup may occur simultaneously with or subsequent to the completion of temperature conditioning. Bootstrap startup begins with initiation of flow through the turbine, and ends when program control has been achieved to initiate thrust buildup. Temperature control shall be maintained during bootstrap, and the engine shall be brought under program control when chamber pressure has reached approximately 60 psia (CP-90290C, 3.1.1.1.5.1.2.1.3).

2.1.2 Reference Engine Requirements

2.1.2.1 Nominal (Ambient Reference) Engine Conditioning Sequence (Reference 1)

At the completion of prestart, the valves, shown in Figure 1, will be in the following positions: PSOV_{1&2}, PDKVA_{1&2}, PDKV_{1&2}, TBV_{1&2}, TDBV_{1&2}, CSOV_{1&2}, and CSCV_{1&2} will be in the closed position. The BBV_{1&2}, BCV_{1&2}, PDCV_{1&2}, PDBV_{1&2}, SSCVs and SSBV_{1&2} will be in the open position. In addition, the drums will be at the zero degrees position. (Figures 2 and 3 show the engine operational phases and control element position during these phases for orientation of the readers to the relation of startup to other phases.)

At the initiation of temperature conditioning, the actuators on PDKVA_{1&2} will continue to remain in the open position. PSOV_{1&2} will be opened to initiate flow into the engine system, and the SSCVs are scheduled in position control to a preset position. The pressure buildup from the opening of PSOV_{1&2} will result in PDKVA_{1&2} and PDKV_{1&2} opening.

FLOW SCHEMATIC FOR 1137400E DESIGN

FIGURE 1

NERVA E-ENGINE REFERENCE DESIGN

FLOW SCHEMATIC

AEROJET NUCLEAR SYSTEMS COMPANY

FIGURE 2

NERVA ENGINE OPERATIONAL PHASES

VALVE AND DRUM POSITION (ENGINE 1137400E)

*NOTE: Dotted Lines Show Motion of One Valve of the Pair.

FIGURE 3

CONTROL ELEMENT POSITIONS

At the start of temperature conditioning, the drums are withdrawn on a time-based position control program of 5 deg/sec for the first 16 seconds, and then at 0.2 deg/sec. The drum ramp is terminated at 94 deg and the drums are placed in position control, holding at 94 deg until detectable heating of the reactor occurs, when temperature control is initiated.

The first portion of the temperature conditioning phase lasts for 120 seconds. This duration is based on preliminary results of heat transfer studies which indicate that the pumps will be chilled sufficiently at this point to produce a positive head if power is applied to the turbines. (This time is an estimate and actual pump condition measurements must be used to establish timing.) During the initial portion of the temperature conditioning phase, the propellant flow through the pump cools the pump surfaces, but it does not effectively chill the balance piston cavity or the pump and turbine bearings. This is adequate for operation below 10,000 rpm without excessive propellant consumption. A pressure rise across the pump is used to accomplish a complete chill. This pressure rise is achieved by opening the turbine block valves and operating the TPA at a relatively low speed in a so-called "powered chill" mode. In Reference 2, a powered chill phase of three minutes at a turbine speed of 6,000 rpm was estimated to be required to complete the pump chillover. Other methods of pump chill are also being investigated for use during the temperature conditioning phase.

Upon receipt of a signal to initiate powered chill, the TBVs are opened fully and the TDBVs are ramped open linearly in four seconds, initiating flow to the turbines. Concurrently, the PDCVs are ramped

linearly from full open to 20% open in one second to increase the pump discharge impedance; the PDCVs are then transferred to closed-loop control on pump speed demand. The BCVs are maintained in the full-open position throughout the powered chill to minimize the turbine acceleration and the peak turbine speed. The control drums are in temperature control.

A bottom limit of 10% on PDCV opening was imposed. A speed demand of 6,000 rpm would require PDCV positions less than 5% open, a region where the valve loss coefficient characteristics are not defined. Speeds in the 7,000 to 8,000 rpm range were achieved at the 10% position, with an SSCV K/A^2 of 17.5 in^{-4} . Towards the end of the powered chill the SSCVs are scheduled inward to prevent a power excursion.

For dual-pump operation, the turbopump design group established a pump Q/N of 0.1 (gpm/rpm) as a preliminary limit for use in analyses. To keep from exceeding this minimum value, during the powered chill phase, propellant was vented from downstream of the pump, at the location corresponding to station 5 in ANSC Drawing 1137456 (Reference 3), back into the tank. After an 8-sec buildup period, the propellant bleed rate was maintained constant at 11.5 lb/sec.

At the end of powered chill (300 sec), closed-loop control is transferred to chamber pressure (P_c) and chamber temperature (T_c), using the PDCVs and drums, respectively, for control. The pressure demand is scheduled linearly to 55 psia at 305 seconds; the corresponding T_c demand at this point is 1350°R. The objective is to move the engine operating point to a position where the propellant bleed from downstream of the pump can be terminated without causing a pump stall condition. The bleed flow is scheduled linearly from 11.5 lb/sec at 305 seconds to zero at 315 seconds.

2.1.2.2 Off Nominal Startup (Restart)

The requirement for off ambient startup

("Startup is initiated upon receipt of a command signal.....", Section 2.0) adds requirements to startup control as follows:

a. Monitoring of Conditions - Timing

of startup functions will be dependent on engine system temperatures (for reactivity and flow distribution), pump chill condition, xenon poisoning, tank pressure and level, neutron level and decay power level.

b. Propellant usage and time requirement

tolerances (Sections 2.0 and 2.1) indicate the need for a "time to start" calculation such that the time from "receipt of a command signal" to "initiation of thrust buildup" may be made conditionally dependent. This will preclude the necessity of excessively long hold times and consequent use of propellant at low Isp (maximize specific impulse, CP-90290B, 3.1.1.5).

c. Cooldown control conditions must be

accounted for in startup timing and calculations to insure compatability and to modify the start sequency and/or profiles.

2.1.2.3 Thrust Buildup Compatability

The engine conditioning phase of startup operation must be compatable with other phases of operation to insure that the requirements of these phases can be met. Specific requirements/constraints of the thrust buildup phase directly affected by engine conditioning are as follows:

a. The engine shall be capable of thrust

buildup through the engine throttle point, and shall maintain rated specific

impulse from the throttle point to steady state operations. For each thrust buildup cycle during the engine useful life, the thrust and specific impulse shall be predictable as a function of time and engine history. The parameters of time, impulse and weight of propellant shall be predictable and controllable from the termination of bootstrap to the completion of thrust buildup in accordance with the limits shown below (CP-90290B, 3.1.1.1.5.1.2.2):

- (a) Time: 24 ± 4 sec (tbv)
- (b) Total Impulse: 714,000 lb-sec $\pm$ 91,250 lb-sec (tbv)
- (c) Propellant: 990 lbs $\pm$ 120 lbs (tbv)

b. The engine shall be capable of operating at any selected point within the operational constraint map shown in Figure 4. During thrust buildup and retreat, the engine shall be capable of chamber temperature ramp rates of $150 \pm 25^\circ\text{R/sec}$ below the throttle point and at chamber pressure ramp rates of 50 ± 10 psi/sec above the throttle point (CP-90290B, 3.1.1.1.3).

c. The control elements (drums, SSCVs, BCVs, PDCVs) must all be within certain positional limits to insure controllability and avoid constraints during thrust buildup (Reference 4). These limits are:

$23 \text{ deg} < \text{drums} < 180 \text{ deg}$ (should be close to 70 deg for nominal conditioning)

$1\% < \text{SSCVs} < 32\%$

$51\% < \text{BCVs} < 74\%$

$38\% < \text{PDCVs} < 53\%$

The values are based on steady state type of data and may be modified by the transient characteristic of startup.

NERVA ENGINE STEADY STATE OPERATIONAL CONSTRAINT MAP

Figure 4

NERVA ENGINE OPERATIONAL CONSTRAINT MAP

2.1.2,4 Shutdown/Cooldown Compatability

The engine conditioning phase of startup must be compatible with and operable from the condition of shutdown/cooldown. The pertinent requirements/constraints from shutdown/cooldown are:

a. The total delivered impulse between the end of throttle hold and the end of cooldown shall be predictable within $\pm 6\%$ (tbv). The total impulse delivered after termination of the steady-state hold at the throttle point shall be controllable to within $\pm 20,000$ lb-sec at termination of cooldown. The time of termination of cooldown impulse shall be predictable within ± 15 sec. Cooldown thrust shall be not less than 30 lb and average cooldown specific impulse shall be not less than 400 sec (CP-90290B, 3.1.1.5.1.4). Termination time, of course, does not apply where startup is initiated prior to termination and the meaning controllability to $\pm 20,000$ lb-sec must be questioned if startup is to occur during the shutdown/cooldown phase.

b. Shutdown/Cooldown Sequence (Nominal - Reference 4) - The nominal sequence of shutdown/cooldown is described here for completeness and to establish the background for compatibility requirements:

1. Pump Tailoff

The drums are transferred from closed-loop to position control and ramped in slowly when chamber temperature demand reaches 2550°R ; PDCV controls chamber temperature past this point. When PDCV reaches a minimum position of 15%, the drums are scheduled in, at their maximum velocity.

During shutdown a transfer is made from two-pump to one-pump operation when the total engine propellant flow rate diminishes to 26 lbm/sec. The objective is to prevent an imbalance wherein one pump would tend to drive the other into stall.

The BCVs are maintained at 100% open during tailoff and the SSCVs are fixed at 2 deg in position control. The pump tailoff mode is maintained until the reactor power decays sufficiently so that flow maintained by tank pressure only can provide further engine cooldown.

2. Cooldown

The cooldown phase begins with the continuation of flow under tank pressure after the termination of pump tailoff. At this point the TBVs and TDBVs are closed, and the PDCVs and BCVs are opened fully. The CSCV₁ and CSOV₁ of the cooldown system are opened to establish liquid hydrogen condition through the cooldown system after which the PSOVs are closed. The SSBVs are closed when the chamber temperature decreases to the lower cooldown limit. This terminates flow to the reflector while structural support coolant flow is continued under CSCV control. Before the temperature of the stem liner material increases to a limiting value, one SSBV is opened to initiate flow through the reflector. The SSBV is closed, terminating the reflector flow, when chamber temperature decreases to a minimum limit. This sequence is continued until the limiting reflector-material temperatures occur before those of the stem liner material. When the minimum temperature limit is attained during this pulse, all flow to the engine is terminated by closing the CSCV. The SSBV remains open.

Successive cooldown pulses are introduced by opening the CSCV when the reflector material temperature increases to the limit. Each pulse is terminated by closing the CSCV when chamber temperature decreases to the minimum cooldown limit.

The cooldown phase is terminated when reactor coolant is no longer required and both the CSCV and CSOVs are closed at the termination of the final flow pulse.

The chamber temperature lower limit has not been established yet and may be a changing value as a function of cooldown condition. The liner material temperature limits may be found in Section 3.4 of TME 2768, S-001 Data Item, November 20, 1970. The reflector temperature limit is 800°R including instrumentation uncertainty.

c. Startup During Shutdown/Cooldown - If startup is called for during the shutdown/cooldown sequence, modification of the performance and/or sequence of control may be necessary or desirable. System limits and general performance requirements of this phase will be maintained. Specific deviations from the nominal shutdown/cooldown and startup are:

1. Pump chill (to the point of readiness for power chill) may be most economically accomplished by providing cooldown flow through the PSOVs instead of through the CSCV/SSBV path. (Allowability of this procedure must be confirmed.)

2. For starts at time periods coincident with peak xenon poisoning, the addition of moderate neutron power at an early stage may preclude startup difficulties but will modify cooldown power profiles. (Again, allowability of this procedure must be checked.)

3. Since the latter phase of shutdown utilizes only one TPA, imbalances in pump chill conditions may exist requiring differential conditioning. Again, as for item 1. above this may be best accomplished with a portion of the cooldown flow.

4. Startup during the latter phases of cooldown may encounter the condition where support system temperatures are relatively low but reflector temperature requires flow. Since reactivity can become excessively high from stem flow at low temperatures, flow through the PSOVs with SSBVs closed can accomplish both the required reflector cooling and a portion of the pump chill with a minimum overcooling of the support system.

5. Startup and shutdown/cooldown calculations for total impulse and time are interactive and a criterion needs to be developed and agreed to as to the tolerances, etc., of these functions.

6. Temperature distribution in the engine is greatly affected by duration and frequency of coolant pulses. The distribution of temperature has large effects on reactivity, the ability to predict criticality and total reactivity, and engine system flows (Reference 5). It may, therefore, be desirable to change the pulse cycle from upper material and lower chamber temperature limits to provide a more favorable distribution. To accommodate this (as well as to provide information for normal cooldown control) an estimate of the total power profile will be required.

7. At steady state, temperatures in the chamber of approximately 1500°R add sufficient heat to the propellant entering the reflector such that the reflector material retains sufficient heat to sustain

bootstrap. The condition must be avoided, however, where the reflector is over-cooled then chamber temperature is raised and bootstrap is immediately initiated. This sequence is a logical result of a condition where; decay heat is high, neutron power is low, the pumps have insufficient heat input-time to require significant chill, and a cooldown pulse has occurred shortly before startup.

8. Tank pressurization flow during steady state and shutdown will normally be sufficient to insure minimum NPSP for bootstrap at the end of cooldown. For a startup during cooldown where significant flow may occur (assuming power chill) the steady-state/shutdown repressurization may need to be modified to account for the early (before end of cooldown) startup.

9. For startup during cooldown, decay heat will form a significant portion of total heat and "detectable heating" (Reference 4) alone is insufficient. It must be insured that a significant portion of the heat is being contributed by neutron power and that specific temperature changes are not just due to temperature redistribution (Reference 5).

2.1.3 Constraints

A number of constraints exist during the engine conditioning phase due either to safety considerations or component limitations of the reference engine.

2.1.3.1 NSS Constraints

See Table 1 for general list of NSS operational constraints and the following specific constraints.

- a. Nuclear Startup (CP-677555, 3.1.1.1.5.1.2.1b)

		Startup Operations					Shutdown Operations					
		Temperature Conditioning			Thru	Buildup						
		Reactor Thermal Conditioning	Nuclear Startup	Engine Temperature Conditioning	Bootstrap	Ramp Up	Steady State Operations	Throttling	Throttle Hold	Temperature Retreat	Pump Tailoff	Cooldown Operations
		1	2	3	4	5	6	7	8	9	10	11
Temperature - °R (°R/sec)												
1. Mixed Mean Chamber, Maximum Graphite Core Composite Core (Trans. Limit)	Maximum	N.A.			4450	4450	4290*	4450	4290*	4450	N.A.	
Comp. Core (Malf. Limit)		N.A.			4358	4358	4290*	4358	4290*	4358	N.A.	
2. Mixed Mean Chamber, Maximum (Rate of Change)	Maximum	N.A.	+175		4378	4378	-	4378	-	4378		
3. Avg. Structural Support Stem Material	Maximum	N.A.	**	**	**	**	**	**	**	**		**
4. Avg. SS Liner Mat'l.	Maximum	N.A.	**	**	**	**	**	**	**	**		**
5. Avg. Support Plate Mat'l.	Maximum	N.A.	800*	800*	N.A.							800*
6. Avg. Reflector Structural Material	Maximum	N.A.	800*	800*	N.A.							800*
7. Avg. Central Shield	Maximum	N.A.	800*	800*	N.A.							800*
Pressures (psi/sec)												
1. Reflector Inlet/Core Outlet ΔP	Maximum	N.A.			820							N.A.
2. Core Axial ΔP	Maximum	N.A.			180							N.A.
Actuator Position (Degrees)												
1. CDDA Position	Maximum	N.A.				TBD	Orificed Angle TBD			N.A.		
Time - Seconds												
1. Maximum	Maximum	TBD				N.A.	36,000	N.A.	36,000	TBD		

* These constraints have instrumentation uncertainties included. The others do not of this time

** Refer to section 3.4 of TNE 2760, S-001 Data Item, November 20, 1970

TABLE 1

NSS OPERATIONAL CONSTRAINTS

- (i) Fission power shall not exceed TBD MW $\pm$ TBD during this phase.
 - (ii) Engine flow rate during nuclear startup $\leq$ TBD lb/sec.
 - (iii) If engine flow is zero, material temperature limits specified for cooldown shall not be exceeded (Table 1).
 - (iv) Reactor period during this phase shall not be less than TBD seconds.
- b. Bootstrap (CP-677555, 3.1.1.1.5.1.2.2)
 - (i) Flow insertion reactivity during bootstrap shall not exceed (TBD) cents.
 - (ii) Control drum shutdown capability shall not be less than \$0.25.
 - (iii) Bootstrap shall not be initiated with fission power $< \underline{\text{TBD}} + \underline{\text{TBD}}$ MW

2.1.3.2 Other Engine Constraints

Engine constraints other than those listed for the NSS in Section 2.1.3.1 are as follows:

- a. Bootstrap
 - (i) Prior to applying power to the turbines sufficient chillover to preclude cavitation and/or stall of one of the TPAs shall be insured by monitoring (TBD) conditions of both pumps.

(ii) Assuming power chill as the reference mode of operation pump speed shall not exceed 10,000 rpm (tbv) prior to achieving the following (TBD) conditions in both pumps. In addition, Q/N (gal/min/rpm) shall not be less than 0.1 (tbv) during this phase.

(iii) Back pressures on the turbine must be maintained consistent with that imposed by the engine to permit thrust compensation by the balancer.

(iv) For additional TPA constraints see S-001 Data Item.

(v) Maximum nozzle wall temperature 1960°R (sustained).

(vi) For additional nozzle constraints see S-001 Data Item.

3.0 MALFUNCTION MODE

Two basic malfunction modes have been defined, "single turbopump" and "component malfunction" where for both modes the engine shall be capable of meeting the following performance requirements when operating under the following malfunction conditions. The engine shall be capable of direct transition to the malfunction modes during any phase of engine operation (CP-90290C, 3.1.1.1.5.2).

3.1 SINGLE TURBOPUMP OPERATION IMPULSE

The engine shall be capable of operating with one TPA valve module inoperative. Operation in this mode shall be initiated or completed as specified for Normal Mode Impulse, or by receipt of a command signal demanding the engine to switch to this mode of operation from the normal mode startup, steady state or shutdown functions (CP-90290C, 3.1.1.1.5.2.1).

a. Startup - The engine shall be capable of the following requirements during single Turbopump startup operation (CP-90290C, 3.1.1.1.5.2.1.2).

b. Engine Conditioning - Engine conditioning shall consist of that portion of startup up to the inception of thrust buildup, namely temperature conditioning, nuclear startup and bootstrap. The engine shall be capable of being temperature conditioned and bootstrapped up to the initiation of thrust buildup within 3 hours (tbv). For subsequent burns following coast periods less than 3 hours, engine conditioning shall not exceed 1 hour (tbv). The propellant consumption during this time shall be less than 380 lbs (tbv). The total time required for these functions shall be predictable within ± 1 second (tbv). A hold period may be utilized to meet this time requirement for engine conditioning. The propellant consumption shall be predictable within ± 40 lb (tbv) (CP-90290C, 3.1.1.1.5.2.1.2.1).

c. Temperature Conditioning - Temperature conditioning is initiated at engine startup and consists of non-nuclear component and reactor thermal conditioning. These operations may be conducted separately or simultaneously depending on engine thermal conditions at startup (CP-90290C, 3.1.1.1.5.2.1.2.1.1).

d. Nuclear Startup - Nuclear startup may occur prior to or simultaneously with temperature conditioning. During nuclear startup reactor criticality shall be achieved (CP-90290C, 3.1.1.1.5.2.1.2.1.2).

e. Bootstrap - Bootstrap startup may occur simultaneously with or subsequent to the completion of temperature conditioning. Bootstrap startup begins with initiation of flow through the turbine, and ends when program control has been achieved to initiate thrust buildup. Temperature control shall

be maintained during bootstrap, and the engine shall be brought under program control when chamber pressure has reached approximately 60 psia (CP-90290C, 3.1.1.1.5.2.1.2.1.3).

3.1.1 Reference Engine Requirements

Requirements imposed by the reference engine design in meeting the system requirements are covered in this section in terms of the changes from Normal Mode operation.

3.1.1.1 Temperature Conditioning

Modification of the Normal Mode temperature conditioning will occur in:

- a. The isolation of the inoperative TPA leg.
- b. Change to the timing and sequence of chilldown flow and nuclear startup.

3.1.1.2 Nuclear Startup

Modification to the Normal Mode nuclear startup will occur in:

- a. Modification to timing.
- b. Changes to control profiles due to modification of system impedances and hence reactivity.

3.1.1.3 Bootstrap

Modification to the Normal Mode bootstrap will occur in:

- a. Isolation of the inoperative TPA leg.
- b. Change to propellant tank bleed (assuming power chill reference) for Q/N control.

c. Modification of control element profiles to account for changes in system gains. (Present data [Reference 4] indicates that modifications may not be necessary.)

3.1.1.4 Thrust Buildup Compatability

Present data (Reference 4) does not indicate a change from Normal Mode requirements, however, potential modifications to requirements are:

a. Change of control element positions for "operable range" during thrust buildup.

b. Modification of "desirable rates" at the time of switch to program control and thrust buildup phase.

3.1.1.5 Shutdown/Cooldown Compatability

No specific requirements changes for the malfunction mode compatability of startup with shutdown/cooldown have been identified except for timing changes.

3.2 COMPONENT MALFUNCTION IMPULSE

When operating with component malfunctions other than those which would cause operation with a single TPA - valve module leg as specified for Single Turbopump Operation Impulse or Emergency Mode Operation, the engine shall be capable of operating under the conditions specified for Normal Mode Impulse (CP-90290 C, 3.1.1.1.5.2.2).

3.2.1 Reference Engine Requirements

With the exception of isolation of the inoperative component, no specific requirements changes for startup have been identified for the component malfunctions studied. The component malfunctions studied are: one SSCV and one BCV. PDCV and drum malfunctions remain to be studied (Reference 4).

3.3 CONSTRAINTS

No modification of engine system constraints from Normal Mode startup have been identified at this time.

4.0 EMERGENCY MODE OPERATION

The engine shall be capable of operation in emergency operating modes. No more than one emergency cycle shall be required of the engine. The emergency operating mode shall be initiated manually or by a command from the malfunction detection and control system or the trend data system demanding the engine to an emergency mode of operation from any point on the engine operating map. The engine shall be capable of a transition to the emergency operating mode during any portion of startup or steady state operation including throttling and throttle hold. For emergencies occurring during shutdown; i.e., after initiation of temperature retreat, the engine shall be capable of cooldown for up to five hours prior to entering the emergency operating mode. The engine shall be preserved in a restartable condition if it can be done at no additional risk to the population, passengers or crew. The engine shall be capable of providing emergency mode impulse at a selected point where $T_c = 3350^\circ R$ (tbv) and $P_c = 200$ psia (tbv) which is within the operational constraint map shown in Figure 2. The minimum emergency

mode impulse and thrust shall be 10^8 lb-sec and 30,000 lb respectively, as specified for Malfunction Operation. Minimum emergency mode specific impulse shall be 500 sec (CP-90290C, 3.1.1.1.5.3).

4.1 REFERENCE ENGINE REQUIREMENTS

No specific requirements for startup control have been identified for this mode.

5.0 THERMAL ENVIRONMENT

The engine shall be capable of withstanding the thermal condition induced during coast and prestart condition for any arbitrary attitude with respect to the sun at 0.72 Astronomical Unit (AU) and shall be capable of withstanding the engine induced thermal condition during transient and steady-state operations within the bounds of engine normal mode, malfunction and emergency mode operation and mission burn times, i.e., 1 hour normal operation at 1 AU, 20 minutes normal operation at 0.72 AU (CP-90290C, 3.1.2.4.2.3).

This requirement will have to be converted to heat input/removal and temperature to define quiescent conditions from which startup must be achieved.

6.0 MALFUNCTION DETECTION AND CONTROL

The engine shall incorporate means for detection of Category II, III, and IV failures (See CP-90290C for definition.). Control logic shall be provided to permit engine operation at maximum performance capabilities consistent with the nature of the malfunction of failure. (CP090290C 3.1.2.7.1.2) While malfunction detection and control is essentially a separate function from startup control, the requirement is listed here to insure that the need for compatibility of startup control design with this function is recognized.

REFERENCES

1. N4130:4548, "NERVA Engine Transients," 7 April 1971
2. N4210:M0620, "Time Required for Pump Chill Prior to Engine Start,"
21 December 1970
3. ANSC Drawing 1137456, "75K NERVA Flight Engine State Point Diagram"
4. NJD-0029, S102-ARCC2-W150, I&C Analysis Report on Engine Controllability,
August 1971
5. RN-S-0510, "Test Data Analysis - Startup Systems," May 1970