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SUBJECT: Engine Cooldown Scoping Study

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(2) Fig 2. Impulse Requirements During Cooldown
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Summary

The performance requirements for engine cooldown are reviewed, and problem areas with the 1137400/E reference engine are identified. Design modifications which might be incorporated to alleviate these problems are evaluated.

Discussion

Cooldown is that phase of NERVA engine operation which begins after initial turbopump shutdown following an engine burn, and during which time the engine must be cooled by expending propellant to dissipate nuclear after-heat. The cooldown phase for the reference engine can be terminated when

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the decay energy level reaches approximately 10 kw. ⁽¹⁾ The cooldown may thus encompass a time period as short as 6 hours for a 20-second full-power burn, or as long as 5.3 days for a 60-minute burn, as illustrated in Figure 1.

The cooldown performance requirements established by the Engine Detail Specification ⁽²⁾ are summarized below:

A. Thrust and Impulse (para. 3.1.1.1.5.1.4)

1. Total impulse delivered after termination of the steady state hold at the throttle point shall be controllable to within $\pm 20,000$ lbf-sec at termination of cooldown.
2. Total delivered impulse between the end of throttle hold and the end of cooldown shall be predictable within $\pm 6\%$ (TBV).
3. Average specific impulse shall not be less than 400 sec.
4. Minimum thrust shall not be less than 30 lbf.
5. Termination of cooldown impulse to be predictable to ± 15 sec.

B. General Requirements

1. Decay power shall be predictable with an accuracy of $\pm 5\%$ (NSS Specification CP-67755).
2. The engine shall be capable of operating with one TPA valve module inoperative (para. 3.1.1.1.5.2.1).

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(1) Superscripts correspond to report numbers in the List of References

3. Cooldown is to be accomplished with propellant supplied at tank pressure conditions as specified in Table 1.
4. The engine shall be capable of restarting at any time during cooldown (para. 3. 1. 1. 1. 1. 6).
5. For emergencies occurring during shutdown, the engine shall be capable of cooldown for up to five hours prior to entering the emergency operating mode (para. 3. 1. 1. 5. 3).
6. The NSS shall have the capability of decay power removal at an average mass flow weighted chamber temperature $> 1450^{\circ}\text{R}$ over the cooldown duration under the condition when the decay power is continuously at the plus 5% accuracy limit. (NSS Specification CP-67755.)

The impulse requirements stated above are also illustrated in Figure (2) for clarification.

Cooldown studies⁽³⁾ conducted for the hot-bleed cycle NERVA engine indicated that the tank pressure cooldown system was preferable at the turbo-pump or the turbocompressor schemes. The cooldown comparison matrix from these studies is included as Table 2.

The tank pressure method was maintained as the preferred cooldown operating mode when the change in the NERVA operating cycle was made from hot-bleed to full-flow. The results of the cooldown study update to the initial full-flow engine design are documented in Reference 1. Basically, the

design considerations for the tank pressure cooldown scheme which was evolved were (a) to maintain engine components within temperature limits, (b) to operate in a manner which precludes development of laminar flow instability (LFI)⁽⁵⁾, and (c) to maximize overall specific impulse, predictability, and controllability of the impulse generated, while minimizing propellant expenditure.

A schematic of the engine flow path is included as Figure 3. From the propellant tank, the colldown flow path is through the CSOV, CSCV, and into the cooldown lines. From this point, a fraction of the total flow can be diverted backwards through the SSCV/SSBV quad-pack to cool the nozzle tubes and reflector. The remainder of the flow continues on into the central plenum of the core support plate and through the structural support elements. The two flow streams then recombine at the reflector exit plenum and continue on to the nozzle chamber along the normal engine flow path.

The principal material temperature limits occur in the reflector and the structural support system. Accordingly, the cooldown is separated into two phases. Initially, a continuous flow of coolant is maintained to the structural support system while the stems are the limiting consideration. The stems are maintained within temperature limits by pulsing flow through the reflector path as required. Later, when reactor power decays below approximately 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 flow paths simultaneously. The reflector material is the limiting factor during this latter portion of cooldown.

Using the basic cooldown scheme outlined above, preliminary studies (6) (7) by WANL yielded the following results which are applicable to the 1137400/E NERVA reference engine:

A. To maintain nuclear subsystem components within temperature limits, the maximum allowable chamber temperature during cooldown is approximately 1650°R.

B. At a tank pressure of 22 psia (minimum for early cooldown), a maximum system flow rate of approximately 1.0 lb/sec can be maintained with both turbine bypass lines open; with one line open, the maximum system flow rate is reduced to approximately 0.6 lb/sec. Both of these flow rates are below the early cooldown flow limit of 1.5 lb/sec, established on the basis of LFI considerations. The chamber temperature would have to be below 1200°R before the 0.6 lb/sec flow could be considered stable. The low propellant flow rates during early cooldown are attributed, primarily, to the change to 4 inch from 7.5 inch diameter turbine bypass lines for the reference engine.

C. During the stem flow only phase of early cooldown, a stem flow rate in the range of 0.25/0.3 lb/sec may be sustained for a time period greater than 300 seconds. This creates a potential LFI situation. Furthermore, these low stem flow rates and attendant high stem exit fluid temperatures produce a potential problem of heating the core support plate to its temperature limit.

D. The 0.25/0.3 lb/sec stem flow rate available with a 22 psi tank pressure might necessitate a quench of the core to maintain stem liner temperature below its limit during early cooldown. A quench to a chamber temperature in the range of 1400°R to 1500°R would be required. This, of course, would adversely affect engine thrust and specific impulse (I_{sp}).

E. As a result of Trade Study 757⁽⁵⁾, chamber temperature during cooldown was expected to remain above 1450°R for 4 to 5 hours before dropping off and asymptotically approaching the reflector limit of 800°R. However, the most recent work⁽⁶⁾ in this area indicates that the time is more likely to be in the range of 1.2 to 1.5 hrs, as shown in Figure 4 (excluding consideration of cool quench as discussed at item D above). The implication of this is that it may not be possible to maintain the average I_{sp} above 400 seconds without generating fission power sometime during the cooldown.

The cooldown studies to date leave two basic questions unanswered: How can cooldown be accomplished with the 1137400/E reference engine? How can cooldown be accomplished within performance requirements?

First, with regards to performance, a method of chamber temperature modulation for controlling impulse to $\pm 20,000$ lb-sec was established in the Post Shutdown Operations Trade Study⁽⁴⁾. This method is still applicable to the reference engine. The requirements to predict the end of cooldown

impulse within ± 15 sec, to maintain cooldown average specific impulse greater than 400 sec, and the ability to predict decay energy level within $\pm 5\%$, are still problematical. The remaining requirements for minimum thrust level, restart capability, and emergency operating capability are deemed feasible.

A number of potential cooldown schemes are outlined below, and a comparison matrix is included as Table 3. The cooldown scheme designated "Pumped Early Cooldown" is feasible for the reference design if the cooldown line/structural support line interface is relocated to upstream of the SSCV/SSBV valve module.

A. Reference Engine

1. Base case - Assume results from the "E" engine cooldown study ⁽⁷⁾ by WANL for a 10-minute engine burn, with no flow throttling during cooldown, as the reference case.

a. Advantages

(1) no additional hardware

b. Problem areas

(1) $I_{sp} \geq 400$ sec may not be achieved

(2) anticipatory control system

(3) number and location of sensors

(4) potential LFI problem

(5) reactor restart(s) may be required to meet $\pm 20,000$ lbf-sec.

- (6) time to reach 10 kw level not predictable to ± 15 sec.

2. Pumped early cooldown - An engine flow rate of approximately 2 lb/sec would be maintained for the initial 800 seconds of the cooldown. Fission power would be provided during this time to maintain chamber temperature in the $1550^{\circ}/1600^{\circ}\text{R}$ range. Power and turbopump would then be shutdown, and cooldown would continue as in base case.

a. Advantages

- (1) no additional engine hardware; but, cooldown line/SSCV line interface moved to upstream of the SSCV/SSBV valve module
- (2) no LFI problem

b. Problem areas

- (1) turbopump control; might require throttling capability for TDBV
- (2) $I_{sp} \geq 400$ sec; however, situation improved compared to base case as far as cooldown, but overall engine I_{sp} decreased
- (3) anticipatory control system
- (4) number and location of sensors
- (5) reactor restart(s) may be required to control impulse to $\pm 20,000$ lb-sec

(6) time to reach 10 kw energy level not predictable to ± 15 sec

(7) reactor control at low power levels

3. TPA brake - The turbopump assemblies would incorporate a brake mechanism which could prevent shaft rotation. The brake would be engaged at the end of pump tailoff. The turbine block valves and control valves could then be opened fully to increase engine flow rates during tank pressure cooldown. Based on a maximum turbine flow coefficient of $0.11 \frac{\text{lbm}(\text{OR})^{1/2}}{\text{lb sec}}$, an estimated additional flow of 0.3 lb/sec/turbine could be added to the engine flow.

a. Advantages

- (1) no LFI problem
- (2) negligible weight addition compared to other schemes

b. Problem areas

- (1) marginal system; potential LFI problem in event of turbine blocking valve or turbine bypass valve failure closed
- (2) increased complexity
- (3) $\bar{I}_{sp} \geq 400$ sec
- (4) number and location of sensors
- (5) anticipatory control system
- (6) reactor restart(s) might be required to control impulse to $\pm 20,000$ lb-sec

- (7) time to reach 10 kw energy level not
predictable to ± 15 sec

4. Pulse with TPA - For reflector overlay pulses during early cooldown, an engine flow greater than the LFI limit of 1.5 lb/sec would be maintained by pulsing (restarting) one turbopump.

a. Advantages

- (1) no LFI problem

b. Problem areas

- (1) turbopump control at low head/speed
conditions
 - (a) might require in-line turbine
control valve
- (2) $\bar{I}_{sp} \geq 400$ sec
- (3) anticipatory control system
- (4) reactor restart(s) may be required to
control impulse to $\pm 20,000$ lb sec
- (5) time to reach 10 kw energy level not
predictable to ± 15 sec

B. Modified Engine Systems

1. Accumulator tank - Engine would incorporate an accumulator tank which is charged with LH₂ propellant. The tank would be pressurized to 40/50 psi range at end of pump tailoff by an auxiliary high

pressure gas bottle(s). The purpose of the tank would be to supply a continuous flow rate of approximately 2 lb/sec for the initial 800 seconds of the cooldown. This scheme is an alternate to the pumped concept A-2, above.

a. Advantages

- (1) no LFI problem
- (2) simpler control compared to pumped
cooldown schemes

b. Problem Areas

- (1) increased complexity; requires additional
valving
- (2) increased system weight
 - a. accumulator tank $\sim$ 900 lbs
 - b. pressurization system $\sim$ 450 lbs
- (3) $\bar{I}_{sp} \geq 400$ sec; however, situation improved
compared to base case
- (4) number and location of sensors
- (5) anticipatory control system
- (6) reactor restarts may be required to control
impulse to $\pm 20,000$ lb sec
- (7) reactor control at low power levels
(10-15 mw)
- (8) time to reach 10 kw energy level not
predictable to ± 15 sec

2. Auxiliary pumping system - System would incorporate auxiliary pumping to provide engine flow rates of up to 10 lb/sec.

a. Advantages

- (1) no LFI problem
- (2) would optimize pumping operations during tailoff (Q/N limit of 0.1 gpm/rpm for main pumps could be maintained)

b. Problem areas

- (1) increased system complexity
- (2) increased system weight
- (3) $\bar{I}_{sp} \geq 400$ sec
- (4) anticipatory control system
- (5) number and location of sensors
- (6) reactor restart(s) may be required to meet $\pm 20,000$ lbf/sec
- (7) time to reach 10 kw decay energy level not predictable to ± 15 sec

3. Additional turbine bypass line(s) - System would incorporate two additional turbine bypass lines to reduce flow impedance.

a. Advantages

- (1) no LFI problem
- (2) minimal increase in system complexity

b. Problem areas

- (1) packaging problem
- (2) additional weight
- (3) $\bar{I}_{sp} \geq 400 \text{ sec}$
- (4) anticipatory control system
- (5) number and location of sensors
- (6) reactor restart(s) may be required to meet
 $\pm 20,000 \text{ lbf/sec}$
- (7) time to reach 10 kw decay energy level not
predictable to $\pm 15 \text{ sec}$

4. Reflector area redesign - Change reflector materials

to increase temperature limits, provide conduction path(s) between reflector and pressure vessel, and optimize insulation thickness between reflector/core.

a. Advantages

- (1) each 17° rise in temperature limit would
save approximately one-hour of cooldown
time⁽⁶⁾
- (2) improved radiative heat transfer ability
would permit terminating cooldown at
higher decay energy levels
- (3) optimized insulation thickness would extend
the time to reach the reflector material
temperature limit, thereby increasing the
average chamber temperature and I_{sp} during
early cooldown

b. Problem areas

- (1) advancement in reflector state-of-art
- (2) introduces one additional component limit
(pressure vessel) during cooldown
- (3) $\bar{I}_{sp} > 400 \text{ sec}$
- (4) anticipatory control system
- (5) number and location of sensors
- (6) reactor restart(s) may be required to meet
 $\pm 20,000 \text{ lbf/sec}$
- (7) time to reach 10 kw decay energy level not
predictable to $\pm 15 \text{ sec}$
- (8) potential LFI problem

5. Dual Mode System (Simple) - System would incorporate a redesigned aluminum reflector barrel to provide a heat removal capability in the order of 200 to 250 kw. This concept would separate the propulsion-mode flow path from the radiator/electric-generation-mode flow path, offering the best dual-mode reliability and least propulsion-mode interference.

a. Advantages

- (1) reduces propellant requirement for cooldown
approximately 56% (10 minute burn)
- (2) reduces cooldown impulse, increasing
effective I_{sp}

- (3) reduces cooldown duration, simplifying trajectory planning
- (4) total system additional weight of approximately 6000 lb offset by increased performance.
Net payload gain probable for Lunar mission.
- (5) could provide tank pressurization energy
- (6) could provide energy for monopropellant RCS system
- (7) could provide stage and payload power

b. Problem areas

- (1) meteorite protection for radiator
- (2) pumping and control system
- (3) LFI problem

6. Dual Mode System (Complex) - System would utilize support stems to provide heat removal capability to power levels up to 500 kw.

- a. Advantages - comparable to Simple Dual Mode, except increased performance gains because of shorter possible cooldown times. Cooldown propellant requirement would be reduced approximately 73% for a 10 minute burn at full power.
- b. Problem areas - major system redesign; otherwise, problem comparable to Simple Dual Mode concept.

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List of References

1. "Post-Shutdown Operations Trade Study for the Full-Flow Engine," ANSC Report No. S054-022, June 1970.
2. "Detail Specification, Part 1, Performance/Design and Qualification Requirements for Engine, NERVA, 75K, Full Flow." C002-CP90290C, August 1971.
3. "Post Shutdown Operations Trade Study for the Hot-Bleed NERVA Engine," Final Report, April 1970.
4. "Post-Shutdown Operations Trade Study for the Full-Flow Engine," ANSC Report No. S054-022, June 1970.
5. Data Item S-54, "Reactor Cooldown Criteria," Trade Study 757, WANL TME-2725, Nov. 1970.
6. "Systems Analysis Summary Report, Nuclear Subsystem," WANL TME-2768, February 1971.
7. "S-001 Update for 400E Engine Configuration," WANL DRM 52966, April 1971.

Figure 1

Fig.2 Cooldown Impulse Requirements

Reference: CP-90290C

Enclosure (2)
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FIG. 3. FLOW SCHEMATIC FOR 1137400E DESIGN

Enclosure (3)
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Figure 4 Comparison of Average Flow Weighted Chamber Temperature Between Results of TS-757 with BCV Throttle and without BCV Throttle for the 1137400 C Engine.

Ref: WIND. TIME 2.706, P. 5-396.

TABLE 1

Tank Pressure Conditions During Cooldown

Reference: Engine Detail Specification #CP090290C, Aug. 1971

<u>Operating Condition</u>	<u>Tank Pressure (PSIA)</u>	<u>Saturation Pressure (PSIA)</u>	<u>Vapor Percent</u>
Normal Operation			
(1) Shutdown & Early Cooldown	22-30	15-30	0
(2) Cooldown (Pulse)	18-30 (TBV)	18-30 (TBV)	0-100 (TBV)
Single TPA			
(1) Shutdown & Early Cooldown	23-30	15-28	0
(2) Cooldown (Pulse)	18-30 (TBV)	18-30 (TBV)	0-100 (TBV)
Component Malfunction Operation			
(1) Shutdown & Early Cooldown	(Same as Normal Operation)		
(2) Cooldown (Pulse)	(Same as Normal Operation)		
Emergency Operation			
(1) Shutdown & Early Cooldown	(Same as Normal Operation)		
(2) Cooldown (Pulse)	(Same as Normal Operation)		

TABLE 2

COOLDOWN COMPARISON MATRIX
FOR HOT-BLEED ENGINE

	Liquid Tank Pressure (POSL)	Ullage Gas Tank Pressure (POSL)	Liquid Turbopumps 7b	Ullage Gas Turbocompressors 7D
Safety Requirements	Satisfied	Satisfied	Satisfied	Satisfied
Reliability (Mission A)	.9973	.9971	.9948	.9948
Comparative Payload Gain, lb				
Change in T_c (Mission B)	Reference	~ No Change	+200	+200
Use of Residual Ullage (Mission A)	0	+2650	0	+2650
RCS	-1000	-1000	-1000	-1000
Hardware	- 180	- 560	- 860	-1260
TOTAL WEIGHT LB	-1180	-1090	-1660	+ 590
Total Change in Equivalent I_{sp} sec (Mission A)	-8.	+8.	-12.	+4.
Principal Components to Be Developed	Valves	Valves	Auxiliary Turbopump and valves	Auxiliary Compressors and valves
Recommended Cooldown System		***		

Reference: "Post Shutdown Operations Trade Study for The Hot-Bleed
NERVA Engine." Final Report, April 1970.

POTENTIAL COOLDOWN METHODS

METHOD	LFI	I_{sp} Avg.	Cooldown Flow Δ (lbs)*	System Weight Δ (lbs)	Mission*** ΔI_{sp} (sec)	Mission*** Δ Payload (lbs)
1. Base Case (E-Engine)	X	X	0	0	0	0
2. Pumped Early Cooldown		X	1680	0	-9.3	-2200
						Provide 2#/sec @ $\bar{T}_c \sim 1600^\circ R$ for initial 800 sec of cooldown. Assumes TPA controllable to $Q/N \sim .05 \frac{GPM}{RPM}$ & reactor controllable in 10 to 15 MW range. Assumes recirculation capability thru cooldown lines.
3. Pulse with TPA		X	565	0	-4.8	-1100
						Assumes TPA controllable @ $Q/N \sim .05$, and recirculation capability to tank thru cooldown line.
4. TPA Brake	X	X	185	200	-2.3	- 700
						LFI problem if valve failure occurs.
5. Accumulator Tank		X	1520	1350	-5.3	-2550
						Provide 2#/sec @ $\bar{T}_c \sim 1600^\circ R$ for initial 800 sec of cooldown. Improved flow control compared to #2 and #3.
6. Auxiliary Pumping System		X	390	960	-4.8	-2060
						Maintain 2.0#/sec min. flow for reflector overlay pulses. Improved flow control compared to #3.
7. Two Additional Turbine Bypass Lines (4" dia)		X	185	270	-2.3	- 770
						Packaging problem.
8. Reflector Redesign	X		-95**	?	+0.5**	+ 100**
						Each $17^\circ R$ rise in reflector limit means ~ 1 hr. less cooldown. ** Based on conduction path to pressure vessel only.
9. Dual Mode (Simple)	X		-1150	2625	+7.5	-925
						Terminate cooldown at 200 KW level.
10. Dual Mode (Complex)	X		-1765	2625	+11.4	- 25
						Terminate cooldown at 500 KW level.

X Designates potential problem

* Based on one 10-min. duration full power burn

*** Mission comprised of six 10-minute full power burns. Payload calculations based on assumption of a constant vehicle lift-off weight of 4.9×10^5 lbm (1.0×10^5 lb payload) and a constant ΔV of 24174 ft/sec.

ENCLOSURE (7)
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