Operating Characteristics and Requirements for the NERVA Flight Engine

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Engine operational characteristics and requirements for typical missions are presented and these are illustrated in detail by a description of the reusable nuclear shuttle operations and requirements. The NERVA nuclear engine has unique conditioning, startup, and shutdown characteristics. In addition, it has a reactor cooldown requirement that is being studied to maximize its usefulness. Shutdown will include a 65% throttled thrust for an optimized period of time to minimize propellant consumption. The reactor life goal is ten hours. Steady-state performance is excellent for future high-energy missions.

Introduction

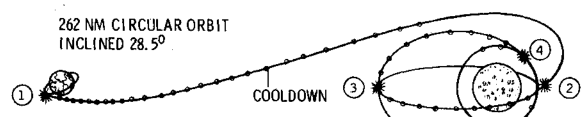
IN testimony[1] before a Congressional subcommittee, M. Klein said, "As NASA and the President's Space Task Group have looked to the future decades in space, the importance of the nuclear rocket has been recognized. One of the prime objectives cited in these views of the future is the need for developing new capabilities for operating in space which emphasize commonality, reusability, and economy. In keeping with this objective, a new space transportation system has been defined which includes a reusable nuclear stage. Specifically, the Space Task Group report refers to: 'A reusable nuclear stage for transporting men, spacecraft, and supplies between Earth orbit and geosynchronous orbit and for other deep-space activities. The NERVA nuclear engine development program...provides the basis for this stage and represents a major advance in propulsion capability.'"

This paper describes the currently defined operational characteristics and requirements of the NERVA engine in relation to reference missions. NERVA technology engine test results and data preceding the current design work have been described.[2,3]

Reference Missions and Reference Vehicle

The current mission requirements for the NERVA design are centered about orbit-to-orbit shuttle and deep-space-probe injection missions, but the engine can perform a variety of manned and unmanned interplanetary fly-by or landing missions. The primary Reference Mission used for NERVA engine requirements and design is a nonoptimum, eight-burn, manned mission to lunar orbit and return (Fig. 1), necessitating many extreme design requirements. An additional reference mission is a four-burn, unmanned mission (A-L-U)§ to lunar orbit and return. Figure 2 shows the lunar payload capability of a nuclear stage, and of the Reference Missions (A-L-M and A-L-U). Figure 2 clearly shows that the Reference Missions for NERVA design are nonoptimum with respect to lunar payload capability. The major factors influencing the reduced payload capability of Mission A-L-M (described herein) are the greater number of burns, short lunar transit times, 10,000 lb of manned shielding, slightly lower mass fraction, and large return payload.

In the A-L-M Mission, the unmanned nuclear vehicle is launched in an off-loaded configuration by means of a Saturn V (INT-21) launch vehicle made up of a nuclear stage (including instrument unit and external engine shield), the launch ascent shell, an empty cargo module, the unmanned personnel module, and an adapter and nose shroud. The



① BURN NO. 1 TRANSLUNAR INJECTION 67 HR TRANSIT
② BURN NO. 2 19 HR ELLIPTICAL ORBIT INSERTION AT 60 NM
③ BURN NO. 3 30° PLANE CHANGE AT 6990 NM
④ BURN NO. 4 TRANSFER TO 60 NM CIRCULAR POLAR ORBIT STAY TIME 9 DAYS

BURN NUMBER →	1	2	3	4	5	6	7	8
FULL POWER DURATION (MIN)	24.9	2.0	0.2	2.2	1.8	0.5	1.5	10.0
COOLDOWN DURATION (HRS)	66.8	9.7	9.8	67.9	7.6	8.0	40.1	84.7

⑤ BURN NO. 5 TRANSFER TO 15 HR ELLIPSE
⑥ BURN NO. 6 46° PLANE CHANGE AT 5880 NM
⑦ BURN NO. 7 TRANSEARTH INJECTION 58 HR TRANSIT
⑧ BURN NO. 8 EARTH ORBIT INJECTION

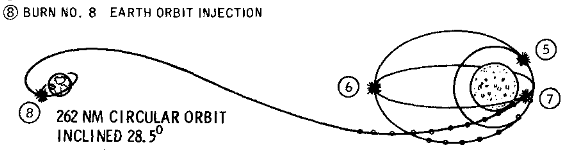


Fig. 1 Lunar-shuttle-mission profile reference case for NERVA engine requirements.

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§ In the mission designations, A is an arbitrary designation for a class of "reusable interorbit shuttle missions" used for engine design studies, L designates "lunar," U designates "unmanned" and M designates "manned."

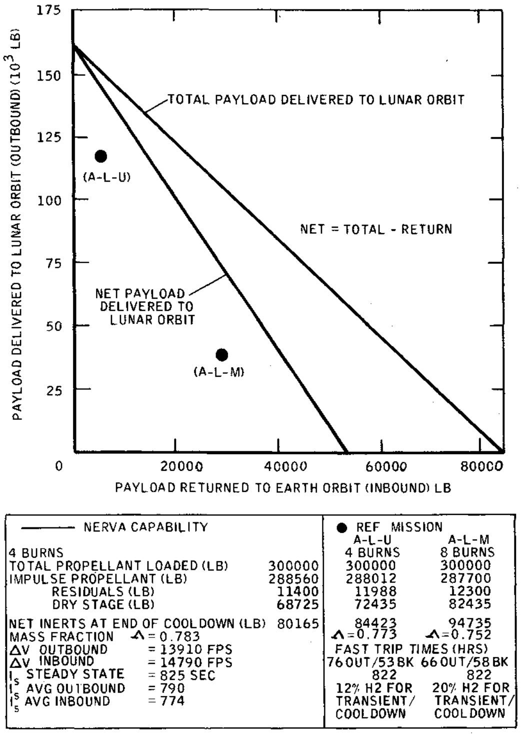

Fig. 2 Reusable nuclear-vehicle lunar payload capability.

nose shroud is jettisoned during the first S-II burn. A second S-II burn injects the nuclear vehicle into a low, near-circular, Earth-rendezvous orbit at an altitude of 262 naut miles and an inclination of 28.5° to the Earth's equator. Local rendezvous and docking with a space station, if required, are accomplished with the reaction control system (RCS) on the nuclear vehicle. Operations at the space station include removal of the ascent shell and the NERVA launch destruct system, functional tests of the nuclear vehicle and personnel module, loading of cargo, boarding of the crew, supply of the RCS propellants and fuel-cell reactants, and filling of the tank with hydrogen. At the appropriate time, the vehicle is separated from the space station by using the reaction control system.

The first burn of the eight-burn mission (A-L-M) places the vehicle on the translunar trajectory. The cooldown thrust is utilized for course correction and attainment of the required velocity increment. The engine is operated through three additional cycles on the outbound flight to 1) enter an elliptical lunar orbit with perilune at 60 naut miles and apolune at approximately 7000 naut miles; 2) change the orbit plane to polar orientation; and 3) achieve gross rendezvous with the lunar-orbit space station in near-circular-polar orbit at an altitude of 60 naut miles. The three-impulse maneuver into lunar orbit is assumed as a potential safety requirement, so failure to obtain thrust at lunar arrival does not result in an orbit from which rescue is impossible or extremely difficult. A portion (10 hr) of the aftercooling

Table 1 Nuclear stage masses for Earth/lunar mission

		Mass, lb
Nuclear stage mass at Earth orbit departure		428,585
Hydrogen (total loaded)	300,000	
Dry nuclear stage	82,435	
RCS and power supply expendables	8,200	
Total load delivered to lunar orbit	37,950	
Nuclear stage mass at lunar orbit departure		227,055
Hydrogen	107,497	
RCS and power supply expenditures	4,108	
Total load delivered to Earth orbit	29,950	

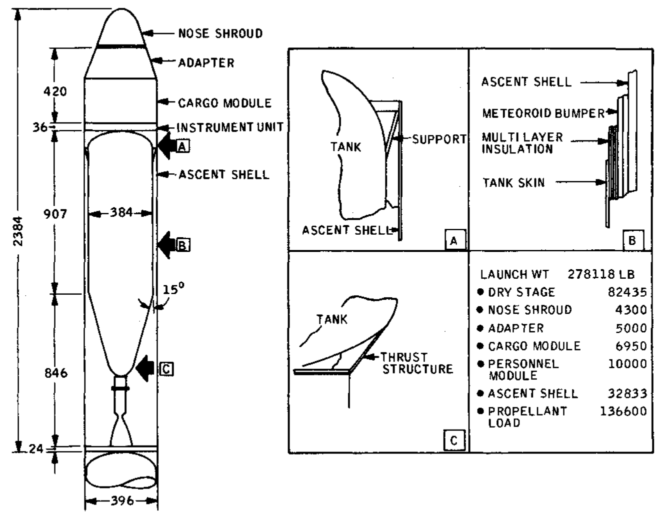

Fig. 3 Nuclear vehicle configuration delivered to Earth orbit.

thrust following the fourth burn is used to achieve gross rendezvous. The RCS is then used to null the additional cooldown thrust and to maneuver the vehicle to docking (if required) with a lunar-orbit space station.

After a stay time of nine days for operations at the lunar space station, the nuclear vehicle is separated from the station by use of the RCS. Departure from lunar-polar orbit utilizes three engine burns similar to those used in the approach. Near perigee of the trans-Earth flight, the engine is cycled for the eighth time to achieve gross rendezvous with the Earth-orbit space station. A portion of the cooldown thrust is utilized to attain the required velocity increment after the eighth burn. The RCS is again used to null the remaining cooldown thrust, and to maneuver the vehicle for docking with the space station.

Operations are then conducted to prepare the vehicle for the next mission cycle. Vehicle mass and payload for the eight-burn mission are summarized in Table 1.

The reference vehicle for the current class of shuttle missions is a single-tank configuration with a 300,000 lb propellant capacity (Figs. 3 and 4).

The tank has a 75° conical bottom to reduce tank heating and to reduce radiation dose to the payload module. The

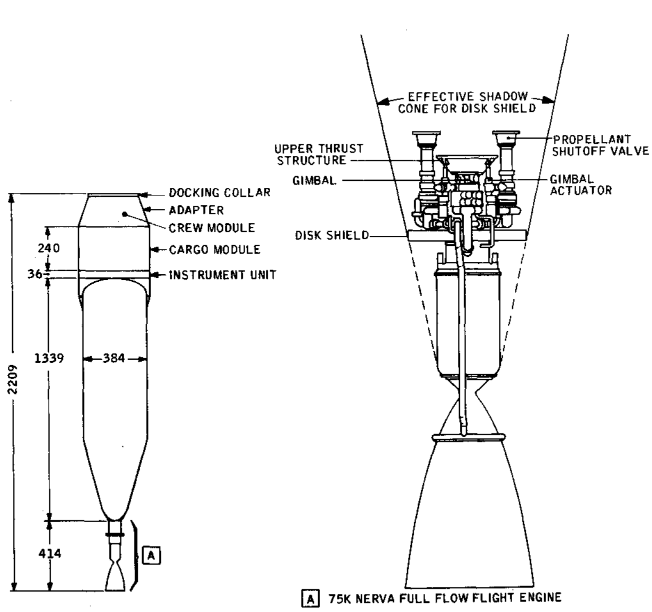

Fig. 4 Nuclear vehicle and engine configured to lunar mission.

tank is protected by a meteroid shield and thermal insulation. During launch, the tank is additionally protected by an ascent shell that furnishes a uniform mating structure with the lower stages (S-II) of the launch vehicle (INT-21) and provides structural support during launch. During launch, the propellant tank is hung from the forward skirt, which mates with the ascent shell. After launch to low Earth orbit, the ascent shell is removed.

During space flight, the propellant tank is structurally linked to the NERVA engine by means of the stage thrust structure that mates to the upper thrust structure of the engine. Reaction control systems are located forward and aft on the vehicle to provide local rendezvous, docking, attitude control, propellant settling, and thrust nulling during the latter portion of engine cooldown. Tank pressurization is provided by hydrogen gas taken from the engine downstream of the turbine and carried to the top of the tank with a pressurization line. The engine controls are located in the vehicle instrument unit compartment forward of the tank, and are linked with the engine by means of a wiring-harness module.

NERVA Functional Requirements and Characteristics

The NERVA engine provides nominal rated thrust and specific impulse of 75,000 lb and 825 sec, respectively. The entire propellant flow, including the turbine drive fluid, passes through the core and is heated to rated chamber temperature before being exhausted through the nozzle. Functional requirements and characteristics are summarized in Table 2.

A simplified block diagram of the engine is shown in Fig. 5. Liquid hydrogen is extracted from the tank at 30 psia. The turbopumps increase the pressure to 1400 psia, after which the bulk of the fluid flows to the nozzle torus to successively cool the nozzle, the reflector, and the peripheral shield. Approximately 10.3 lb/sec is diverted into the reactor structural system. The gas expands through two low-temperature turbines, with some 7.4 lb/sec of turbine bypass flow to provide for control reserve. The turbine exit gas and bypass fraction are recombined, heated in the reactor to 4250°R, and expanded through a nozzle to develop thrust. Pressurization

Table 2 Summary of NERVA functional requirements/characteristics

Engine flow cycle	Full flow
Nominal rated conditions (Normal Mode)	
Propellant delivered at tank outlet	28 psia saturated propellant (LH_2, 0% vapor)
Thrust	75,000 lbf
Specific impulse	825 lbf-sec/lbm
Chamber pressure	450 psia
Chamber temperature	4250°R
Nozzle expansion ratio	100:1
Engine weight w/o external shield, max	24,500 lb target
Engine weight with external shield, max	34,500 lb target
Endurance	
Cycles	60 cycles
Total duration	600 min at rated temperature
Startup and shutdown	
Nominal temperature rate	150°R/sec
Nominal pressure rate	50 psia/sec
Operating line	Through throttle point 4250°R/293 psia
Startup conditions	Anytime at 15 psia tank, saturated LH_2, 0% vapor)
Shutdown throttling	4250°R/293 psia as required by mission
Cooldown	
Minimum average specific impulse	400 lbf-sec/lbm
Minimum thrust level	30 lbf
Thrust nulling	None (design option)
Controllability tolerances	
Steady-state specific impulse	$\pm$0.75% with specific impulse trim
Steady-state thrust	$\pm$2.0%
Reliability	
Reliability	0.995 to meet all normal mode functional and endurance requirements
Substitution of maintainability	No substitution for reliability
Diagnostics	Trend data
Safety	
Man-rated	Eliminate single failures that endanger personnel
Anticriticality	Provide means of preventing accidental criticality
Destruct system	For launch and ascent

Engine flow cycle	Full flow
Single turbopump malfunction mode	
Specific impulse	Same as normal mode (825 lbf-sec/lbm)
Thrust	60,000 lbf at 2 psia NPSP, 28 psia saturation
Startup, shutdown, throttling, and controllability	Same as normal mode
Emergency mode	
Minimum specific impulse	500 lbf-sec/lbm
Minimum thrust	30,000 lbf
Minimum total impulse	10^8 lbf-sec in single cycle
Detection	Diagnostic instrumentation
Tank pressurization	
Engine supplied	Autogenous from engine during startup, steady-state, and shutdown
Thrust vector control	
Displacement	3 deg
Velocity	0.25 deg/sec
Acceleration	0.5 deg/sec
Electrical power from engine	None
Shielding	
Internal shield	Protect engine components
External shield	Disk shield to limit dose to 10 rem
External shield weight	0–10,000 lb max
External shield removal/reinstall	Complete removal/reinstall in space
Maintainability	
Location	Ground and space
Separation from vehicle	Remote capability
Engine layout	Modularized components
Leakage	Less than 400 SCI/min—nonoperating
Environment	All ground, launch, and flight environments
Storage	
Ground	5 yr
Launch pad	6 months
Space	3 yr
Transportability	Any attitude—land, sea, or air
Cleanliness	Particulate distribution up to 600 μ level

gas, as required, is fed to the stage tank from a location downstream of the turbine.

The endurance requirement includes up to 60 burn cycles of various lengths, totaling a minimum of 600 min at rated conditions. Thus, the engine will be able to complete ~12 shuttle-class missions before its useful life is expended. The limiting factor in the useful life is expected to be the corrosion loss of nuclear fuel from the reactor core. Because reactor life is temperature-dependent, a compromise must be reached between rated specific impulse and useful life.

The rated thrust level is sufficient to provide the multiple-mission capability while still allowing maximum utilization of existing facilities.

Transient Performance and Controllability

The propellant feed system must be capable of starting and operating with saturated propellant at the inlet to the engine. The engine is started and shut down at nominal temperature and pressure ramp rates of 150°R/sec and 50 psia/sec (max), respectively. The temperature rate is the max allowable within thermal-stress limitations of the reactor. To conserve propellant with the limited temperature ramp rate, the engine is started to rated specific impulse (825 sec) and 65% thrust (49,000 lb) before proceeding to full thrust. The temperature and pressure conditions corresponding to the above intermediate point are 4250°R and 293 psia (the throttle point).

Propellant is conserved during shutdown by reducing the thrust to the throttle point before ramping down the temperature. More importantly, a short hold (1–3 min) at the throttle point during shutdown results in a reduction in propellant

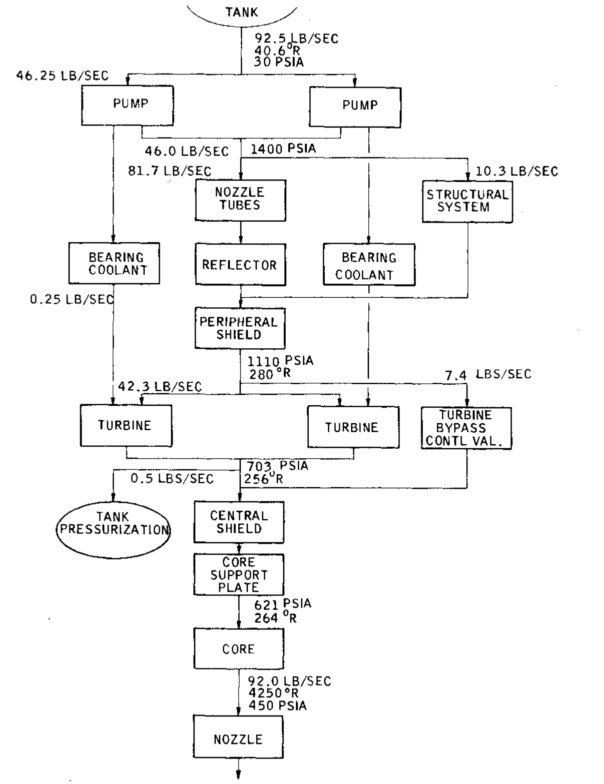

Fig. 5 Engine block diagram, normal mode operation.

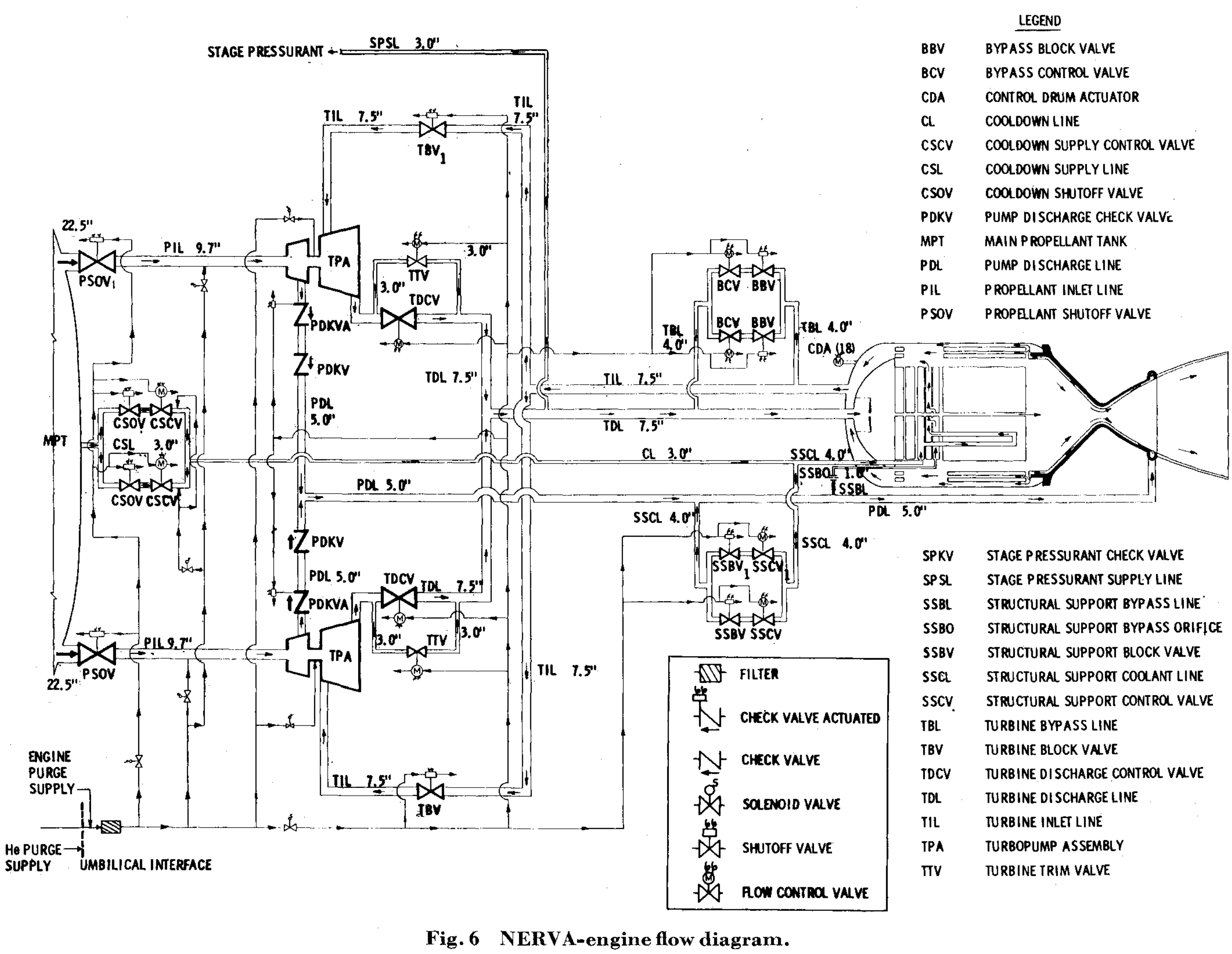

Fig. 6 NERVA-engine flow diagram.

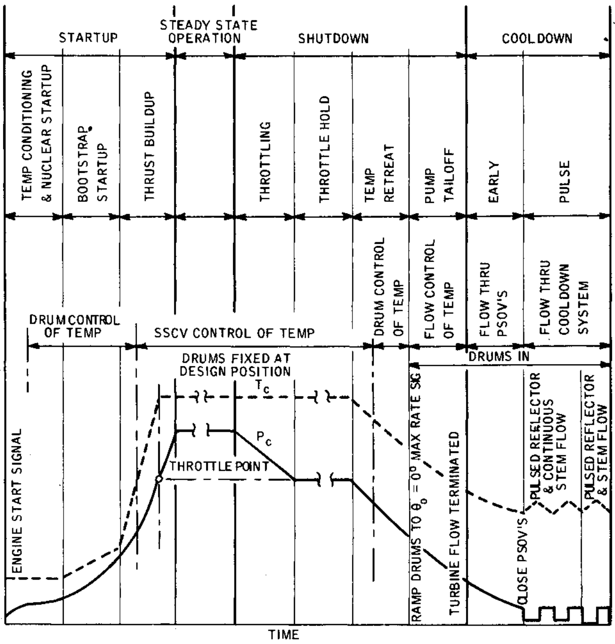

Fig. 7 NERVA-engine operational phases.

consumption for delayed neutron power and fission-product decay heat absorption.

After completing the shutdown transient, the engine must still be cooled because of the heat released from fission-product decay. The cooldown flow driven by tank pressure is controlled by the cooldown supply system and the structural-support coolant system (SSCS) independently of the main propellant feed system. Reactor internal structural constraints limit the I_{sp} level of the cooldown to between 400 and 500 sec. The minimum thrust during the cooldown flow is maintained above 30 lb to remain within the sensing capability of the guidance accelerometers, based on the need to utilize as much as possible of the cooldown impulse.

There is currently no thrust-nulling requirement for the engine, and it is assumed that any necessary thrust nulling will be provided by a reaction control system on the vehicle. However, thrust nulling by the engine could be provided below a power level of ~75 kw.

Reliability and Safety

The NERVA engine reliability requirement of 0.995 will meet all normal mode functional and endurance requirements, but does not allow substitution of mantainability for reliability.

The engine is to be man-rated, which requires elimination of single failures or combinations of failures that could endanger personnel, including the launch crew, flight crew, or general public. As a result of the reliability and safety requirements, the engine includes many redundant systems, as shown schematically in Fig. 6, including redundant propellant feed systems.

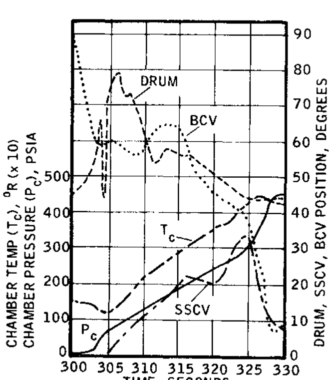

Fig. 8 Engine bootstrap and ramp to rated power with 24 psia tank pressure.

Single Turbopump Malfunction Mode and Emergency Mode

If one leg in the propellant feed system (PFS) malfunctions, the engine must be capable of extending operation to complete the mission at rated specific impulse and at a thrust level of approximately 60,000 lb. The 60,000-lb thrust level is the level which can be obtained with a fixed turbine configuration without further constraining the engine design or increasing engine weight beyond that for the normal mode. During a PFS malfunction, the remaining operating leg undergoes a flow swing from approximately 46.0 to 73.3 lb/sec. Current engine design does not include boost pumps or special low-speed inducers for accommodating the flow swing; therefore, a net positive suction pressure (NPSP) of approximately 2 psia must be provided to achieve the full malfunction thrust capability of 60,000 lb.

In addition to the single turbopump malfunction mode, the engine must provide a capability for emergency mode operation. In this situation, the objective is to continue flight to a safe rescue orbit, as opposed to completing the mission. Diagnostic instrumentation must be provided on the engine for detecting incipient failures that could lead to a required emergency mode operation. In the emergency mode, the engine must be capable of providing a minimum specific impulse of 500 sec, a minimum thrust of 30,000 lb, and a minimum total impulse of 10^8 lb-sec in a single cycle.

Tank Pressurization

The engine must be capable of supplying pressurization gas to autogenously pressurize the tank during startup, steady-state operation, and shutdown transient. This capability significantly increases the vehicle performance by eliminating the need for a heavy pre-pressurization system on the stage. The pressurant is bled from downstream of the propellant feed system turbines.

Thrust Vector Control and Electrical Power

The engine is required to provide gimbal thrust vector control, as shown in Table 2.

All actuation power (including power for control drums, valves, and gimbal actuators) is required to be electrical, but there is no requirement for the engine to supply its own electrical power. This is because a large requirement for electrical power occurs during the long duration of the cooldown period, which the present engine cannot provide. It might be noted, however, that an advanced concept being studied for use in later generations of the engine would use engine thermal power during cooldown and thereafter, as required, to generate electric power. This advanced system would reduce cooldown propellant consumption from current requirements, and would also allow an early cooldown thrust termination.

Shielding

The engine has internal shielding in the pressure vessel to protect engine components. In addition to the internal shielding, provision is made for an external disk shield as required for manned missions. The external shield must be designed for complete removal and reinstallation in space. This permits either manned or unmanned missions, without imposing a performance penalty when the external shield is not required. The external shield weight is strongly dependent upon the vehicle and payload configurations. The engine design provides for external shields up to 10,000 lb in weight.

Maintainability

The engine is being designed for maintainability both on the ground and in space. The current design calls for a single separation plane to allow the engine to be remotely replaced on the stage, thus increasing the useful life of the stage. In addition, the various subsystems of the engine are being modularized to simplify replacement of failed components on the engine.

Additional requirements for leakage, environment, storage, transportability, and cleanliness are shown in Table 2.

Engine Operational Phases

Conditioning

The various normal engine operational phases are shown schematically in Fig. 7. Conditioning of the engine components is done to prepare the engine for a satisfactory bootstrap. This conditioning consists primarily of chilling the turbopumps, achieving reactor criticality, and (if the reactor is not already warm) increasing the reactor temperature to the bootstrap starting level.

When restarting from a cooldown phase, the reactor temperature will be approximately 1400°R while other components (such as the nozzle and reflector sections) will be in a chilled condition. For example, for the Earth-lunar shuttle, the reactor will be at 1300–1400°R upon arrival at the Moon, and thereafter during cooldown while maneuvering into a lunar polar orbit. If departure occurs immediately after jettisoning payload, the reactor will still be warm. If, however, the vehicle is allowed to stay in lunar orbit for extended periods, such as 30 days, the reactor temperature conditions will be low. In either case, the engine will be readily startable. The NRX/EST (Reactor Experiment and Engine System Test) and XE (NERVA Experimental (Engine) test series have demonstrated that the engine can be started with a variety of initial conditions and startup control concepts.

For vehicle operations, an interesting aspect of conditioning is that the hydrogen flow can be considered as useful for settling propellant in lieu of (or in addition to) auxiliary propulsion devices. The chamber temperature at the end of chilldown can range between 850 and 1500°R. These temperatures correspond to specific impulses of 340 and 470 sec, respectively, which are quite competitive with chemical systems. Thrust levels are variable and reach a level of about 900 lb.

Bookstrap and Thrust Buildup

The bootstrap of the pumping system and the ramp up to full power is illustrated in Fig. 8, showing a typical sequence of engine conditions following a 300-sec engine conditioning period with 24-psia tank pressure. At the start of bootstrap, the temperature is maintained constant at 1500°R under temperature-loop control, using the reactor control drums. The propellant shutoff valves, the turbine bypass control valves and blocking valve, and the structural system blocking valves are wide open. The structural system control valves are at minimum open position, while other valves are closed.

The bootstrap is initiated by demanding a 60-psia chamber pressure with the pressure being controlled in a closed-loop mode by the bypass control valves. The turbine inlet and outlet valves are opened. As the increased flow tends to decrease the chamber temperature, the drums roll out until the pump output starts to increase very rapidly. Then the drums roll back in to correct for the rapid increase in hydrogen neutron moderation effect. This rollback is reversed again at the end of bootstrap in response to the various effects of hydrogen moderation and temperature demand.

It should be noted that the valve actions here described are typical. Other valve arrangements and sequences of valve actions are possible and are being studied to arrive at the optimum type of operation.

Thrust buildup is initiated when the chamber pressure arrives at 60 psia, and the engine is ramped up a normal operating line which imposes a demand temperature ramp of 150°R/sec until the throttle point is reached. At this point chamber pressure is 293 psia, corresponding to a 49,000-lbf thrust level and temperature is at rated 4250°R, corresponding to an I_{sp} of 825 lbf-sec/lbm. From the throttle point, temperature is held constant and chamber pressure is increased at 50 psi/sec until rated pressure and thrust (450 psia and 75,000 lbf, respectively) are reached to complete thrust buildup. Chamber pressure is controlled with the bypass control valves, which control turbine power. Temperature is controlled by the reactor control drums up to 3000°R and is thereafter controlled by the structural system control valves, which regulate the density of hydrogen within

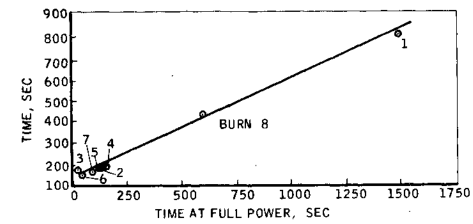

Fig. 9 Time, pump tailoff plus early cooldown phases, Mission A-L-M.

Table 3 Steady-state design point conditions

	Flow, lb/sec	Pressure, psia	Temperature, °R
Tank outlet	92.5	30	40.6
Pump outlet (each)	46.0	1400	59.3
Structural system inlet	10.3	1390	59.4
Structural system outlet	10.3	1120	564
Nozzle tube inlet	81.7	1370	59.4
Nozzle tube outlet	81.7	1180	191
Reflector bypass outlet	7.0	1120	252
Reflector outlet	74.7	1120	243
Peripheral shield outlet	92.0	1110	280
Tank pressurization gas	0.5	703	256
Main turbine inlet (each)	42.3	1070	280
Main turbine outlet (each)	42.6	735	256
Turbine bypass valve inlet	7.4	1080	280
Turbine bypass valve outlet	7.4	706	280
Core inlet	92.0	621	264
Core outlet	92.0	450	4250

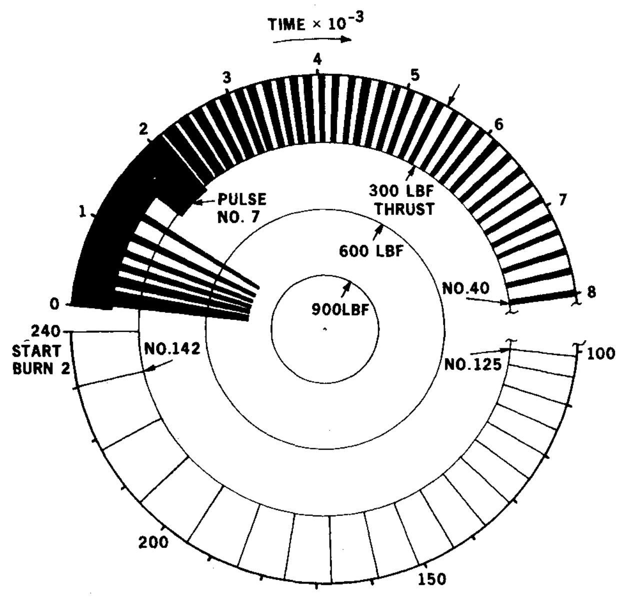

Fig. 10 Typical cooldown thrust and pulse pattern, Burn 1, Mission A-L-M.

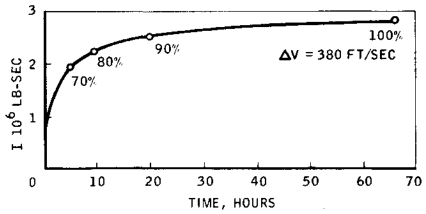

Fig. 11 Pulse cooldown impulse, Burn 1, Mission A-L-M.

the reactor. The drums are then ramped on a 1.5 deg/sec rate to a rated operation position.

In addition, the engine will also have supplied, by the end of the startup phase, the pressurization gas needed to bring the vehicle propellant tank to its design operating pressure.

Steady State

Steady-state conditions are summarized in Table 3. Maximum pressure level is 1400 psi at the pump discharge location. Temperatures vary; initial conditions at the storage-tank outlet are those for liquid hydrogen, whereas temperature at the reactor core inlet is 264°R, and the final, nominal, average mixed chamber temperature is 4250°R. Tank pressurization gas is bled from the engine at the turbine outlet at 256°R temperature.

Shutdown

The shutdown phase starts with a chamber pressure decrease from 450 to the 293-psia throttle point at a rate of 50 psi/sec. The engine holds at this point for various time periods, which are mission dependent. Throttle thrust level is 49,000 lbf. In a gravity force field, the lower thrust can cause a vehicle performance loss, but this type of loss is offset by a decrease in propellant consumption for cooldown. During this retreat phase the control drums are fixed and the temperature is controlled by the structural system control valves.

The retreat from the throttle point is done with a shutdown temperature ramp rate of 150°R/sec. Chamber pressure decreases at approximately 11 psi/sec. Temperature control is principally accomplished with the reactor control drums, which rotate in until they reach their zero angular position, which is at conditions of approximately 2800°R chamber temperature and 175 psia chamber pressure; pump tailoff thus being initiated with temperature control by means of pump flow rate. Flow is controlled to produce an exponential-type chamber temperature profile. When the temperature decreases to the maximum cooldown limit, the temperature is held constant by continued turbopump operation until the flow requirement decreases to a level at which cooldown can be continued under tank pressure only. At this point, the turbopumps are shut down to terminate the pump tailoff phase and to initiate early cooldown.

During early cooldown, the cooldown system valves are opened, allowing liquid hydrogen flow conditions to be established in the cooldown system. When the chamber temperature decreases to the lower pulse cooldown operating limit, the propellant shutoff valves close to terminate shutdown.

Table 4 Throttling cost benefits

Σ Time at throttle point, sec	350
Δ Payload to lunar orbit, lb	1,340
EOS delivery costs, $/lb	100
Lunar delivery costs, $/lb	400
Lunar Δ payload value, $	536,000
Engine life penalty, $	58,000
Net gain per flight, $	478,000

The time between start of pump tailoff and shutdown is relatively long. Figure 9 presents a plot of this time as a function of time at full power for a typical eight-burn mission.

Throttling Economic Advantages

For the Earth-lunar space transporation system, over-all operational economy is a prime objective; selection of the throttling feature in the NERVA engine is an example of the use of cost criteria. Table 4 summarizes the results of a preliminary throttling cost study. The mission considered was Earth-to-lunar orbit and return to Earth orbit using a total of four engine burns and assuming stage (minus engine) lifetime of 30 round trips. The cumulative time at 65% throttle point was 350 sec per flight, and the net gain in payload delivered to the Moon was 1340 lb. For an Earth-orbit-shuttle payload delivery cost of $100/lb, the corresponding payload delivery cost into lunar orbit is $400/lb. A cost penalty occurs because the throttling operation causes an engine life degradation. Thus, Table 4 includes a cost penalty for this factor. The net-cost benefit is approximately $500,000 per flight, which over a large number of flights would make throttling economically worthwhile.

Pulse Cooldown

The final phase of engine operations is pulse cooldown. The nuclear-decay-heat release is relatively significant during the first few hours of pulse cooldown and then tends to exist at low levels for long time periods thereafter. The temperature requirements in the engine are currently under study. However, the maximum chamber temperature is anticipated to be somewhere around the 1400–1700°R range for the early pulse cooldown conditions. To put the cooldown propellant requirements into perspective relative to the other operational phases, Table 5 is shown. This table shows the typical hydrogen consumption for an eight-burn Earth-lunar shuttle mission. The total hydrogen required for cooldown is 5.76% of the initial 300,000 lb. The cooldowns after Burns No. 1 and 8 are by far the most demanding, consuming 43% and 19%, respectively, of the cooldown hydrogen.

Figure 10 illustrates the cooldown operations during the long cooldown of Burn No. 1 of the above mission. The

Table 5 Nuclear vehicle 300,000 lbm hydrogen allocation and total ΔV possible during pulse cooldown phases, Mission A-L-M

All engine phases		% Total Loaded
Rated power operation		79.31
Transients		12.39
Startups	3.16	
Shutdowns	9.23	
Cooldown		5.76
Residual		2.54

Pulse cooldown phases

Cooldown period	Total ΔV available, fps	% Total cooldown propellant expenditure
1	380	43
2	70	7
3	40	4
4	70	8
5	75	6
4	55	4
7	120	9
8	340	19

decay-energy release at shutdown is approximately 6.5 Mw and at the end of 66.8 hr, 8 kw. To conserve hydrogen, the decay heat is absorbed primarily by discrete mass-flow pulses operating within a 100°R temperature band. However, some continuous flow of hydrogen at low-mass flow rates is used to keep the reactor structural support elements from overheating during the early part of pulse cooldown. Later, this continuous flow is terminated, and there will be long periods of zero-flow plus discrete pulses of flow. In Fig. 10, the small continuous flow is 0.40 lb/sec (thrust = 190 lbf) from start of cooldown to the seventh pulse which occurs 0.44 hr later. The large pulses, which are superimposed on top of the continuous flow, have a total of 1.7 lb/sec flow rate (thrust = 790 lbf) until the seventh pulse, after which it is changed to 0.70 lb/sec. The pulse frequency is very low at the end of cooldown, as illustrated. This pattern of pulses can be varied considerably by changing maximum and minimum temperature limits and, therefore, should be considered as only illustrative.

The impulse characteristics of cooldown are illustrated in Fig. 11 for Burn No. 1, which was discussed above. This shows the effect of the rapid rate of energy release during the very early stages of cooldown relative to the later times. The total impulse during this cooldown amounts to 2.8 million lb/sec (or 2.35% of the total impulse of Burn No. 1). The maximum ideal velocity increment is 380 fps. Most of the cooldown impulse (90%) is realized in the first 20 hr of cooldown operation. The cooldown impulse is considered as part of the useful impulse, and in the above case (leave-Earth burn), it can be considered to be similar to an extended velocity trim system that that could be useful for trajectory correction purposes. After other burns, when approaching Earth or lunar rendezvous orbit, it can be used to gradually trim into the desired orbital position. The nuclear shuttle is assumed to have a chemical reaction control system that will be used for precise rendezvous and docking maneuvers.

Summary

Various potential missions are being studied to determine NERVA engine requirements; one of the most demanding is the Earth-lunar reusable-nuclear-shuttle, eight-burn mission. Ultimately, the reusable nuclear shuttle may be serviced and supplied by a low-cost, Earth-to-orbit, reusable chemical shuttle; but for design purposes, it is presently assumed that Saturn launch vehicles and Saturn derivative nuclear stages will be used. However, the long-range objective of low cost is influential in reaching current design decisions, as illustrated in the selection of an engine throttling mode. Other chararcteristics of the engine design are a specific impulse of 825 sec at a thrust level of 75,000 lb; a 10-hr lifetime with up to 60 restarts; restart capability at any time; zero-NPSP dual pumps for supply-tank pressures of 15 to 30 psia; capability of supplying tank pressurization gas; high-accuracy controls; thrust-vector control; man-rating; 0.995 reliability; five-year ground and three-year space storability; propellant-feed-system malfunction mode; emergency abort mode for flight safety; and space maintenance of critical items.

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An Active Radiation Shield for Cylindrically Shaped Vehicles

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An effective magnetic shield design has been developed for protecting a cylindrical space vehicle from space electron radiation. It employs a few coils of equal diameter (and approximately twice the vehicle diameter) located coaxially about the vehicle. The magnetic shield simulator (MAGSIM) has been used to develop engineering data for designing this shield. The data are presented nondimensionally and can be used to design a cylindrical shield of any size; as an example, an active shield for a 10-ft-diam, 30-ft-long vehicle is designed, assuming a current density in the superconductor of 2.5×10^5 amp/cm² at 10°K. This shield protects against electrons with a 7-Mev cutoff energy, produces ~500 gauss inside the vehicle, and weighs 525 lb.

Introduction

A MAJOR hazard of manned space travel is radiation damage to both the crew and some electronic components of the vehicle. For many Earth-orbit missions, the principal radiation hazard is that of the natural and artificial radiation belts composed of trapped relativistic electrons and high-energy protons. Because of the tremendous weight penalty imposed by passive material shields and the potential weight savings afforded by active electromagnetic shields, numerous studies of active shields have been made, with promising results.[1–3] Their advantage over material shields is greatest when the radiation hazard is limited to the relativistic electrons. The relatively low mass of the electron makes it easy for moderately intense magnetic fields to deflect electrons away from the vehicle, and thus the hazardous bremsstrahlung radiation that is produced in any material shield (and requires additional massive shielding) is precluded in active

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