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A PRELIMINARY STAGE CONFIGURATION FOR A LOW PRESSURE NUCLEAR THERMAL ROCKET (LPNTR)

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Abstract

A low pressure nuclear thermal rocket (LPNTR) is configured to meet the requirements of a nuclear stage for manned Mars exploration. Safety, reliability and performance are given equal consideration in selecting the stage configuration. Preliminary trade studies are conducted to size the engine thrust and determine the thrust chamber pressure. A weight breakdown and mechanical configuration for the selected LPNTR concept are defined. A seven engine stage configuration is selected which gives a two engine out capability and eliminates the need for engine gimbaling. The stage can be ground assembled and launched as a unit including tankage for trans Earth injection and Earth orbital capture. The tankage is configured to eliminate the need for an inert shield. The small engine will be cheaper to develop than a single engine providing full thrust, and will be compatible with stages for Earth orbital, Lunar and deep space missions. Mission analyses are presented with engine operation in a high thrust mode and in a dual range high thrust-low thrust mode. Mass savings over a reference NERVA stage are projected to be 45-55% for the high thrust operating mode and 50-60% for the dual range mode. Potential exists for further increases in performance by optimizing the thrust chamber/nozzle design.

Background

Two prior papers[1,2] have provided a description and performance estimate for the INEL low pressure nuclear thermal rocket concept as well as background information on nuclear rockets operating at low (e.g., <50 psia) chamber pressure with hydrogen propellant. In these papers a baseline engine operating at a high thrust chamber temperature (>3200 K) and a low thrust chamber pressure (~20 psia) was projected to produce a specific impulse of ~1250 s at an engine thrust to weight of about 6:1. In this paper, additional engine studies are presented and the engine is configured for integration with a stage which fits the general requirements defined by NASA for a manned Mars mission.

Reference Engine

The general configuration, internal concept, and fuel module for the reference LPNTR are shown on Figs. 1-3. The core is spherical with 120 fuel modules evenly spaced around the sphere. The core is held together by a central metal structure which mates to the stage through the flange at the top of the reactor (Fig. 2). Two beryllium half shells are attached to the central structure and the fuel modules are attached to the beryllium. The reference nozzle configuration (Fig. 1) is based on stage constraints as defined in the stage section. On Fig.1, stage pressurization lines are shown for information. The reference engine concept operates on tank pressure and it will be necessary to maintain tank pressure during operation by using the engine to heat hydrogen. A concept has not been defined for this system, but it is anticipated the neutron and gamma heating external to the reactor will be sufficient to heat the hydrogen.

Propellant flows under tank pressure into the nozzle exit cone, cools a portion of the nozzle and the pressure vessel. It enters the core through passages in the central core structure and exits through the individual fuel modules into the thrust chamber. A by-pass flow enters the reactor through the center of the core structure and diffuses uniformly into the hollow central cavity for reactivity control. The central cavity has flow passages permitting the reactivity control hydrogen to join the main hydrogen flow prior to entering the fuel modules. A poison rod can also enter the central flow passage for additional safety during launch or during shutdown periods.

From the central cavity the propellant flows between the beryllium core structure and the outer frit of the particle fuel bed as shown on Fig. 3. The flow enters the fuel bed through an outer frit, flows axially across the particle fuel, and exits through an inner frit and flows radially out through the central cavity of the fuel module. Matching power and flow in the fuel module is a critical design consideration and INEL is considering fuel wafers, refractory foams, wire screens, etc., as alternates to the fuel particles. These will have poorer heat transfer characteristics and may force larger cores with a somewhat lower engine thrust-to-weight.

The heat transfer studies on the reference particle bed concept are based on a projected heat transfer augmentation as indicated by Bussard[3] and reproduced on Fig. 4. Additional heat transfer data with dissociating hydrogen in conjunction with improved materials properties data are needed to make a final decision on fuel f rm.

Projected performance, design data and weight estimates for the reference engine are summarized on Table 1. Performance is projected at both 3200 K and 3600 K. The 3600 K column only indicates those values that are different than those for the 3200 K thrust chamber temperature.

Preliminary Reactor Analysis and Trade Studies

In the prior studies on the LPNTR[1,2] it was indicated the reactor would operate at a maximum average core exit temperature of 3200 K. This was based on studies at the end of the NERVA program indicating the feasibility of using an all carbide fuel element consisting of a mixture of uranium and zirconium carbide. Mixtures of hafnium or tantalum and uranium carbide have the potential to operate at higher temperatures, but the neutronics in the NERVA core made the use of these materials appear unfeasible. The spherical core proposed by INEL for the LPNTR has more favorable neutronics and a preliminary study has been conducted to assess the feasibility of higher operating temperatures.

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The fuel model used for analysis is shown on Fig. 5. It is similar to the baseline model, except the inner 10% of the fuel bed and the inner frit is assumed to consist of a hafnium 180-uranium carbide mixture. The fuel loading is assumed to be 0.5 g U235/cc over the entire bed and a k_{eff} of 1.054+/-.020 was obtained indicating a sufficient margin for reactor criticality and control. The available data indicates hafnium melts about 400 K higher than zirconium and assuming the structural properties of the materials are represented by the melting points, it is assumed a 3600 K thrust chamber temperature is feasible. It will be necessary to obtain additional materials property data to verify this assumption. Fig. 6 shows a typical power density and temperature distribution radially through a particle bed fuel assembly with 1 mm diameter particles.

In order to select an engine size for the stage trade studies described in the next section, it was necessary to estimate how engine parameters change as function of the thrust level. Estimated changes in key parameters are indicated in Figs. 7 and 8. The parameter changes for a fixed engine size (core ID/OD=35/70 cm) are indicated by Fig. 7, where the changes in power density and chamber pressure are approximately proportional to thrust increases. The engine T/W increases to about 20:1 at a thrust of ~60,000 lbf, and then levels off. The theoretical specific impulse is also fairly well leveled off by the time the 60,000 lbf thrust is reached: The principal gains in theoretical specific impulse are most significant below about 30,000 lbf thrust.

For the parameter changes indicated on Fig. 8, the reactor size is changed while the chamber pressure remains fixed at 15 psia. Note that the engine thrust/weight ratio is estimated to remain approximately the same (T/W=6) as the engine thrust is increased a factor of four (from ~11,000 to ~44,000 lbf). For this comparison, the nozzle length was kept constant to prevent the size from getting too large. This resulted in a reduction in area ratio and specific impulse as the chamber pressure was increased. Many additional parametric analyses can be done to assist in selecting an optimum engine/nozzle configuration but time and funding constraints did not permit additional work to support this paper.

Figures 7 and 8 show the specific impulse for shifting and frozen equilibrium. As mentioned in prior papers[1,2], there is a great uncertainty in the kinetics of hydrogen dissociation/recombination in the core-thrust chamber-nozzle system. For the performance analysis presented later in this paper, the TDK code[4] is used to estimate specific impulse. This code indicates only minor gains in specific impulse as pressure is dropped for the conventional thrust chamber nozzle arrangement used in the baseline concept (Fig. 1). The code does, however, indicate that non-conventional arrangements would improve specific impulse and additional study is needed in this area. The data base supporting the hydrogen model in the TDK code is inadequate and additional kinetics data for hydrogen dissociation/recombination are needed before additional optimization studies would be meaningful.

Preliminary Stage Concept

A preliminary stage concept using the LPNTR has been defined using the general guidelines supplied by NASA for manned Mars exploration at the nuclear thermal propulsion workshop[5]. A schematic of the stage concept is shown on Fig. 9. The stage produces 75,003 lbf thrust with seven LPNTRs each producing ~10,600 lbf thrust. The decision to use seven engines in the stage configuration illustrated on Fig. 9 is qualitative based on the following considerations;

- A single engine configuration is considered to be absolutely unacceptable from the standpoint of safety and reliability. A two engine out capability was selected based on indications this was being considered as a requirement for the Lunar transfer vehicle.
- A seven engine configuration was selected because the failure of any two engines would leave at least three aligned for thrusting through the center of the stage. This is sufficient thrust for all maneuvers except for trans Mars injection, (TMI) and with the perigee pulsing for TMI, the mission can be aborted after the failure of any single engine.
- The smaller engines will be much cheaper to develop and ground test.
- The smaller engines will be easier to configure into a stage for orbital transfer, Lunar or deep space exploration missions. Versatility will be an important cost factor in the final selection of any propulsion system for space transportation.
- The nuclear stage which fits within the 30 x 10 m envelope shown on Fig. 9 can be ground assembled and launched as a single unit, eliminating the need for space assembly.
- The stage as shown has a disk shield above each engine to meet a requirement for the NASA NTP workshop[5]. Shielding analysis at INEL indicates this will not be required using the configuration shown on Fig. 9. The Earth Orbital Capture (EOC) tanks have been configured to retain sufficient propellant to provide shielding during the high power portion of the EOC burn. After Earth orbital capture is complete the propellant remaining in the tank can be used for final cooling of the reactor. As the reactor cools less shielding is required and at all times sufficient astronaut protection is provided without the need for the dead weight shield.
- The stage configuration also has the potential advantage that it may be possible to move all control and electronic hardware to the top of the EOC tank. This is illustrated on Fig. 10. The LPNTR does not require the transmission of hot hydrogen to drive a turbine and with only the non-compressible legs of liquid hydrogen in the center of the EOC tank, it should be possible to control thrust and power from above the tank. This will substantially decrease the radiation to the control valves and associated electronics giving an increase in the reliability of the control system.

With the engine constrained to a 10,700 lbf thrust and the nozzle limited in length and exit area a final trade study was made to select an operating pressure. The chamber pressure was reduced from 35 to 7 psia by opening the nozzle throat to maintain thrust. This resulted in a decreased the nozzle expansion ratio and the TDK code was used to estimate the resulting specific impulse. The results are shown on Fig. 11. Fifteen psia was selected for the reference engine.

Mission Analysis

The seven engine LPNTR cluster stage is compared to NERVA derivatives for the NASA 2016 NTR Reference Mission[6] using several different LPNTR performance levels as shown on Table 2 For the high performance option, it is assumed that the LPNTR chamber pressure and thrust are reduced a factor of 5 below their normal full power level, with a resulting increase in specific impulse to 1350 s. The NERVA engine could be reduced to forty percent thrust at full operating temperature and it was arbitrarily assumed that without the problem of pump stall, the LPNTR could be reduced an additional 20%. The increase to 1350 s specific impulse is not predicted by the TDK code. It is based on predictions by Bussard and others as summarized in the prior papers[1,2]. The mission analysis results, Table 3, indicate mass savings of 281 to 866 MT or 45 to 60% for the various scenarios analyzed.

Summary

The radial flow low pressure nuclear thermal rocket has potential to give the maximum performance which can be obtained from a solid core nuclear thermal propulsion engine. It has neutronics which are favorable for operating with the highest melting materials known at the present time. The specific impulse is maximized by operating the reactor at pressures and temperatures which are favorable for the dissociation of hydrogen. The recombination of hydrogen as the pressure is dropped in the thrust chamber-nozzle system has the potential to further increase the specific impulse from the engine. A specific impulse of 1050 s which has been estimated for operation at 3200 K with a 15 psia thrust chamber pressure and a 40:1 expansion ratio nozzle is a minimum performance estimate for the concept. A specific impulse over 1300 s is a reasonable target for an optimized engine operating at a maximum temperature.

The studies summarized in this paper show that a practical stage can be assembled using clustered low pressure engines. In prior studies on the concept[1,2] it was shown that many potential reliability and safety problems can be eliminated by operating at low pressure. Tables 4 and 5 summarize these advantages relative to a high pressure engine. The improved performance of the LPNTR results in substantial mission advantages. On the reference NASA mission for Mars exploration the concept can save up to 60% of the initial mass in low earth orbit. It is concluded that development of a low pressure nuclear thermal rocket should be a priority task for the U.S. space program.

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Performance

Thrust	10,700 lbf	10,700 lbf
Chamber temperature	3,200 K	3,600 K
Chamber pressure	15 psia	
Engine thrust weight	~6	
Specific impulse, TDK	1050 sec.	1210 sec.

Engine Design Data

Engine system - pressure fed (no pumps)		
Engine mass	1,840	
Nozzle throat diameter	22 in	
Nozzle length	205 in	
Nozzle area ratio	40	
Flow rate	10.5 lb sec	9.1 lb sec
System pressure drop	20 psi	

Reactor Data

Thermal power	260 Mw	
Fuel region power density, av	5 Mw lit	
Reactor geometry	Spherical shell	
Flow direction	Radial-outward	
Fuel material	UC-ZrC	+ 180 HfC UC
Fuel form	1mm beads or wafers	
Fuel matrix melting point (max)	~3700K (ZrC)	~4200K (HfC)
Fuel density in fuel	1 g 235 U/cc	
Fuel loading	~40 kg 235 U	~50 kg 235 U
Fuel assembly type	Conical - axial/radial/axial flow	
No. of fuel assemblies	120	
Film ΔT,	11K at fuel exit	
ΔT in bead (1mm dia.)	25K at fuel exit	
Max fuel temperature, nominal	3636K at fuel exit	

Reactor core ID/OD	**35cm/70cm**
Reactor moderator	**Be + ZrH**
Reactor reflector	**Be + graphite**
Reflector thickness	**10cm**

Engine Mass Estimate (3200K)

Reactor

Region	Material	Mass kg
Hot Frit	ZrC foam	3
Fuel	ZrC coated beads	158
Cold frit	Zr	7
Moderator	ZrH	123
Moderator	Be	70
Reflector	Be + graphite	332
	Reactor subtotal	693
Nozzle		43
Propellant lines		34
Thrust chamber		20
Auxiliary equipment		45
	Total mass	835 kg (184[illegible])

Table 1 - 11,000 lbf Thrust LPNTR

Assumptions — 7 engine configuration
— No losses for reduced thrust after earth departure
— Shield 10mt

Mission	Thrust	Thrust Chamber Pressure	Thrust Chamber Temp	Isp Equilibrium	Isp Frozen	Isp Used for Analysis
Low performance	75,000#	15	3200	1190	1012	1050
Med performance	75,000#	15	3600	1400	1122	1210
High performance	75,000# [1]	15	3600	1400	1122	1210
	15,000# [2]	3	3600	1540	1170	1350

[1] Earth departure
[2] All other burns

Table 2 - LPNTR Mission Analysis

Engine	Isp	T/W Engine	T/W Engine plus shield	Mission Ref IMEO	Mission 500 km Earth Orbit IMEO
Ref (NERVA)	850	4	2.8	884	1400
Advanced NERVA	925	6	3.3	713	1037
LPNTR 3200 K	1050	6	2.2	603	814
LPNTR 3600 K	1210	6	2.2	485	611
LPNTR 3600 K Dual range	1210 1350	6 1.2	2.2 0.44	440	534

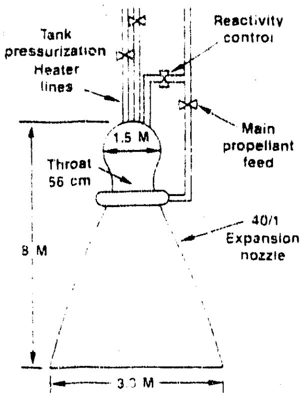
Table 3 - IMEO Advantate LPNTR

Explosive rupture	— No pumps - operates below tank pressure
Reactivity insertion	— Mechanical drums eliminated
Loss of flow	— Engines can be manifolded to get emergency flow from all tanks

Table 4 - LPNTR Reduces Susceptability to Safety Critical Failures

• Potential to reduce or eliminate troublesome components	Turbo pump — eliminated Control drums — eliminated Engine gimbal — eliminated Valves — reduced Reactor parts — reduced
• Small engine size gives 2 engine out capability	Any two failures of 7 engine configuration
• Low pressure reduces thermal problems	Dissociation/recombination helps retain core heat transfer at low pressure. Lower nozzle and thrust chamber heat flux
• Reduced radiation	Control valves and electronics above run tank

Table 5 - LPNTR Reliability Potential



- Concept designed to maximize flow at low pressure & high temp

Features
Radial outflow core
Particle or plate fuel
Operates on tank pressure
Reactivity power control

Performance
Thrust 10,700#
Weight 1840#
T/W ~ 6/1
Isp ~ 1050-1210 @ full thrust
~1350 @ low thrust

Fig. 1 - Reference LPNTR

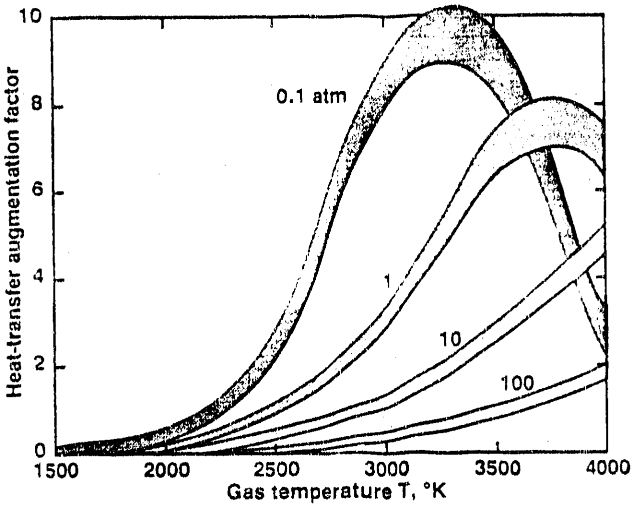


Fig. 4 - Estimated Augmentation Factor for Dissociation-Recombination Effects in Convective Heat Transfer to Hydrogen (Bussard 1985)

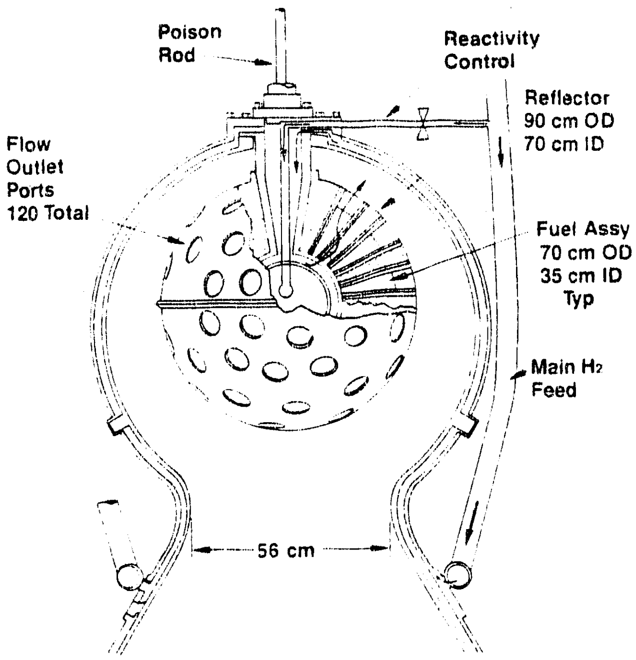


Fig. 2 - Preliminary LPNTR Internal Configuration and Flow

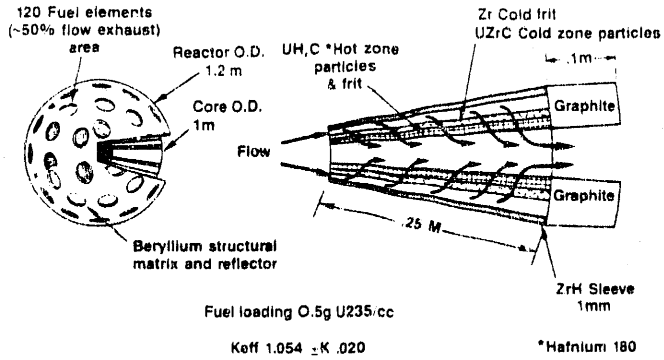


Fig. 5 - Preliminary LPNTR Neutronic Study Results

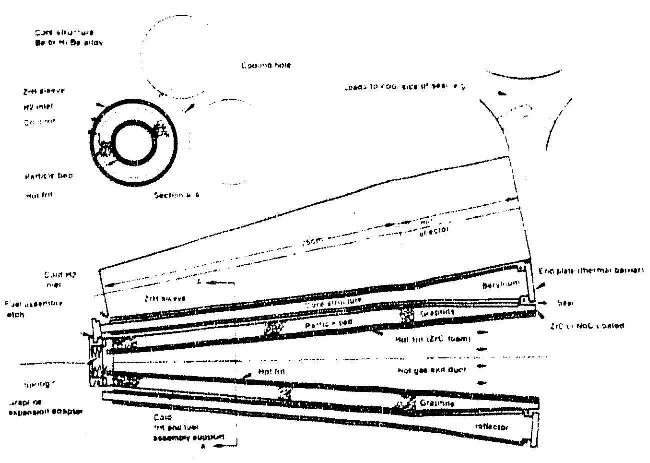


Fig. 3 - LPNTR - Particle Bed Fuel Assembly Schematic

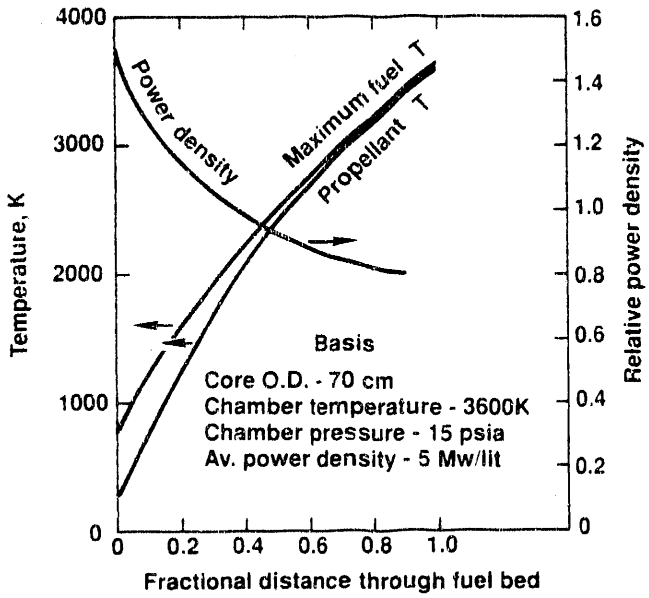


Fig. 6 - LPNTR - Fuel Bed Power Density and Temperatures (11,000 lbf Thrust)

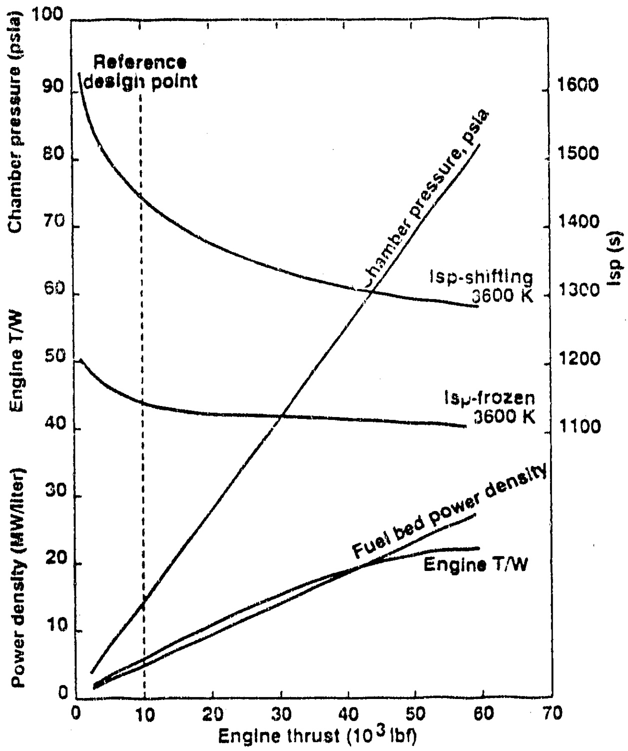


Fig. 7 - LPNTR Thrust Increase
(Fixed Engine Size)

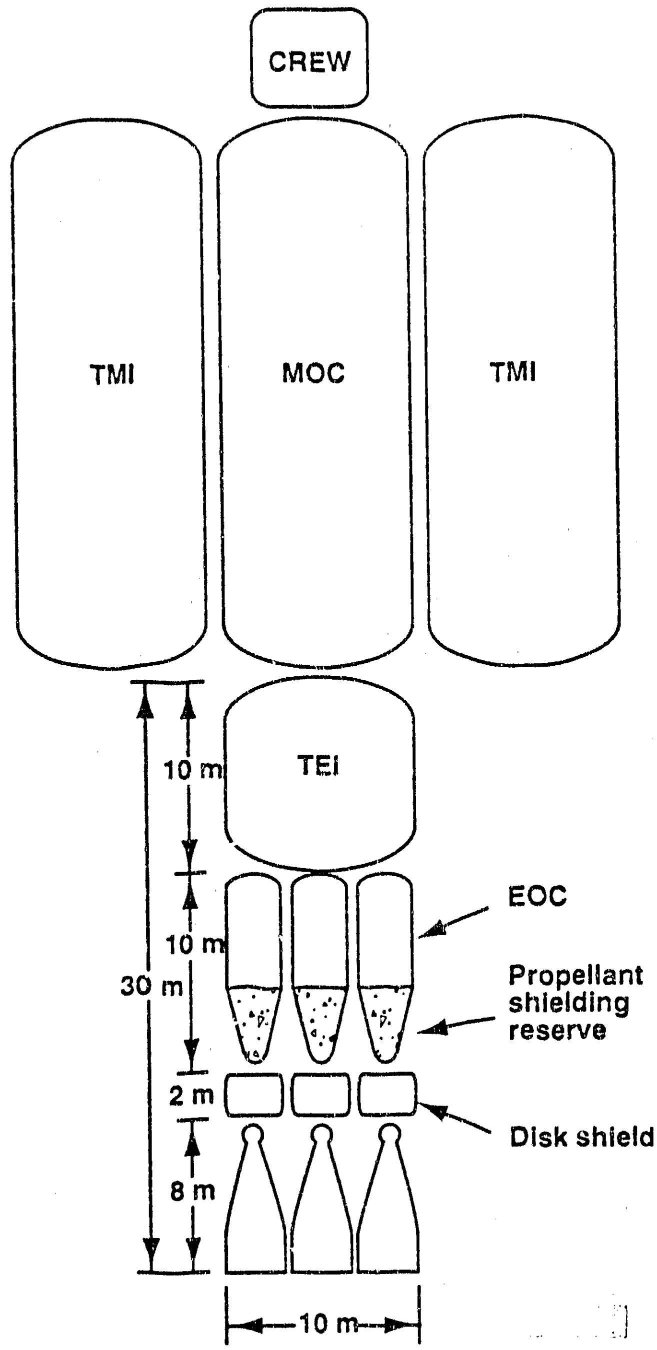


Fig. 9 - Tank and Engine Configuration
for Mission Analysis

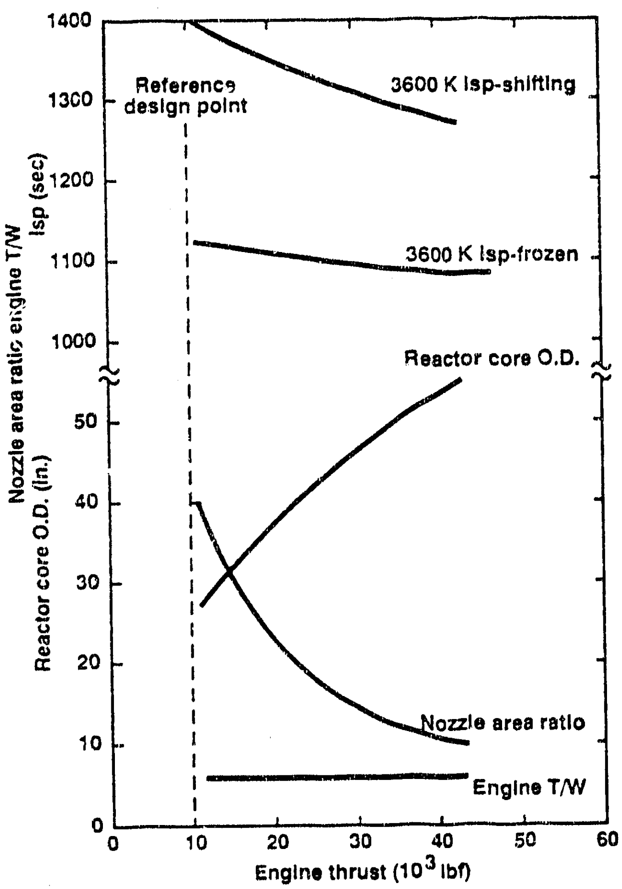


Fig. 8 - LPNTR Thrust Increase
(Fixed Chamber Pressure)

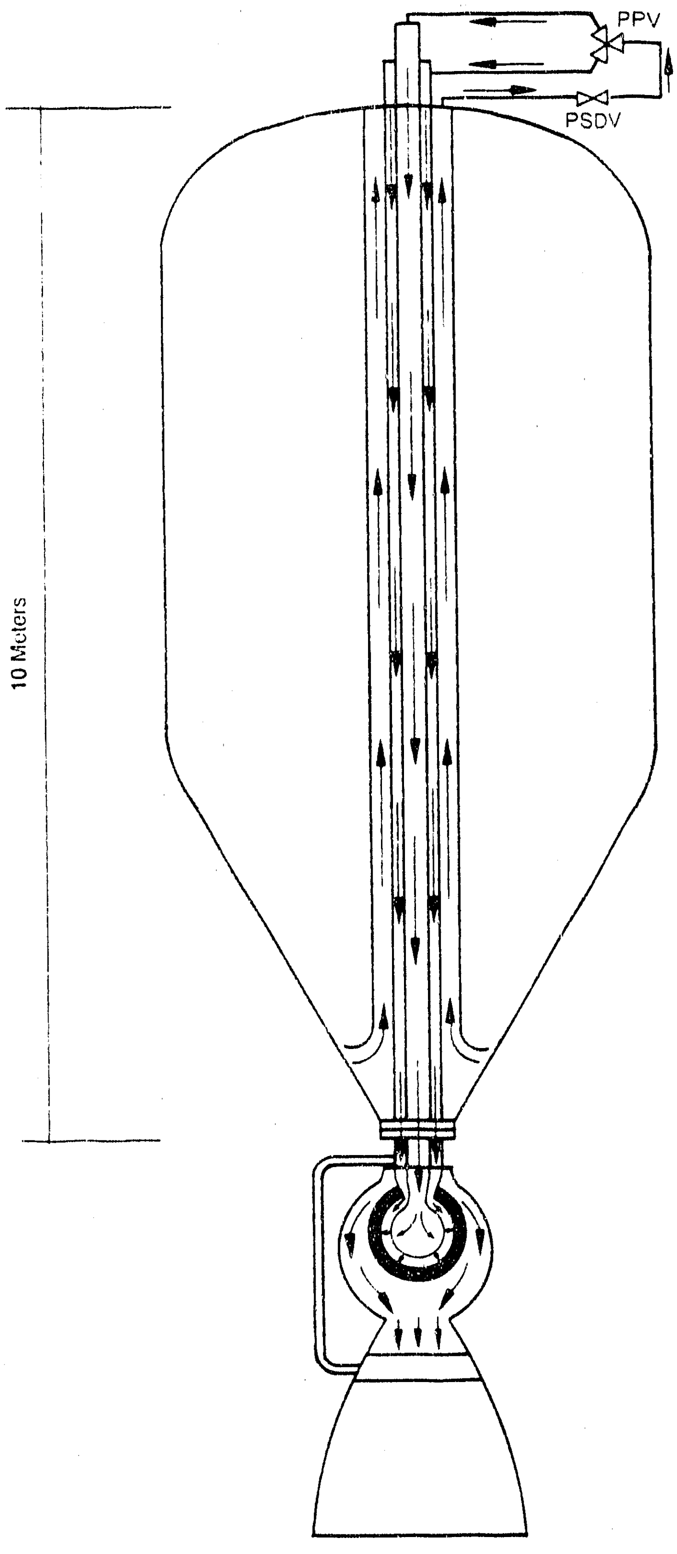


Fig. 10 - Schematic - Remote Valve LPNTR

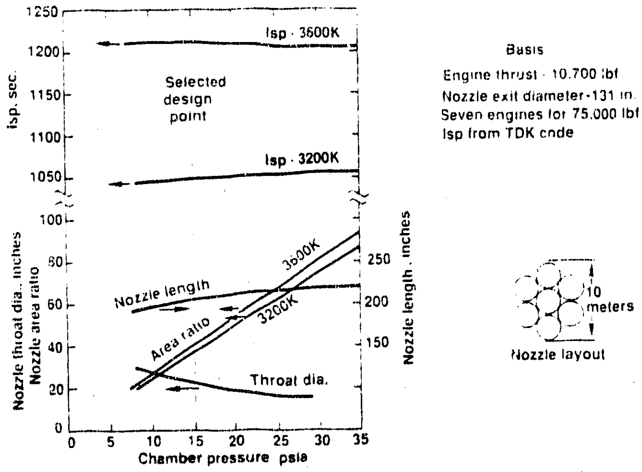


Fig. 11 - Seven-Engine LPNTR Cluster-Nozzle Trade-Offs

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