Performance Potential of the Colloid Core Reactor Concept in Near-Earth Applications

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An Air Force research program has produced performance estimates for the colloid core nuclear reactor rocket engine concept. These values are parametrically varied to determine their individual influence on an advanced nuclear upper stage to the Space Transportation System. Pessimistic and optimistic performance of the concept is estimated. The concept is compared with other propulsion schemes on the basis of velocity capability (as an indication of performance) and the mass which must be initially boosted into orbit (as an indication of cost). Based upon the analysis, it is concluded that the concept warrants further consideration for development as a future operational system.

Nomenclature

a = tankage fraction
b = engine thrust-to-weight ratio
c = shield constant, lbm/ft^2
D = reactor diameter, ft
EOS = Earth-to-orbit-shuttle
g_0 = acceleration of gravity, 32.176 ft/sec^2
IMEO = initial mass in Earth orbit
I_s = specific impulse, lbf/lbm per sec
M_{bo} = vehicle mass at propellant burnout
M_{crit} = reactor nuclear fuel critical mass
M_e = rocket engine mass, T/b
M_f = nuclear fuel mass
M_0 = initial mass of the vehicle
M_p = impulsive propellant mass
M_{res} = propellant reserve
M_{sd} = propellant loss during reactor shutdown
M_{sh} = nuclear shielding mass, cD^2, proportional to reactor surface area
M_{pay} = payload mass
M_{st} = structural mass
M_{su} = propellant loss during reactor startup
M_t = tankage mass, $a\ M_p$
n = number of burns to be performed
OOS = orbit-to-orbit shuttle
T = engine thrust, lb
ΔV = velocity increment, fps
λ = nuclear fuel loss rate, lbm/sec
τ = total engine burn time, sec

Introduction

THE concept of the Colloid Core Nuclear Reactor (CCNR) has been under investigation for several years at the Air Force's Aerospace Research Labs.[1,2] Such a reactor uses dustlike uranium alloy particles in a vortex flow cavity which is externally moderated. The vortex is driven by the tangential velocity component of the injection fluid (hydrogen in the case of nuclear rocket applications). The centrifugal force of the flowfield reduces loss of the particles out the exhaust nozzle. Like the open-cycle gaseous core reactor,[3] propellant is mixed directly with the nuclear fuel. The superior heat-transfer characteristics of such reactors allow the engines to have a high ideal specific impulse without the fuel element structural limitations of solid core reactors. The projected specific impulse of the CCNR engine is approximately 1100 sec. Engineering studies of the CCNR concept[4,5] have indicated that relatively high thrust-to-weight ratios (~5 : 1) at relatively low thrust levels (20,000 lbs) are feasible, which leads to a potential performance advantage for cis-lunar space operations.

The evolution of the joint NASA/DoD Space Transportation System (Space Shuttle) prompts one to consider the performance of the CCNR rocket engine when applied to the upper stage (Orbit-to-Orbit Shuttle) of the system. Vehicle performance parameters will be varied to determine their individual influence on mission potential. Following this variation optimistic and pessimistic performance is estimated and evaluated for typical OOS missions between a 100 naut mile parking and geosynchronous orbit.

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Parametric Performance Variations

The effect of varying vehicle performance parameters is readily determined from the rocket equation. Gravity losses are to be neglected. Therefore

$$\Delta V = g_0 I_s \ln (M_0/M_{bo}) \tag{1}$$

where the total vehicle mass may be broken up into its many components

$$M_0 = M_p + M_t + M_e + M_f + M_{sh} + M_{st} + M_{pay} + nM_{su} + nM_{sd} + M_{res} \tag{2}$$

The nuclear fuel requirement is the reactor critical mass plus that fuel which must be replaced because of vaporization and failure of the chamber to contain particulate fuel without loss out the exit nozzle.

$$M_f = \lambda\tau + M_{crit} \tag{3}$$

$$= \lambda M_p I_s/T + M_{crit} \tag{4}$$

Equation (1) may be rewritten in the form

$$\Delta V = g_0 I_s \ln \left\{\frac{M_0}{M_0 - M_p[1 + (\lambda I_s/T)]}\right\} \tag{5}$$

where

$$M_p = \frac{M_0 - (T/b) - cD^2 - M_{crit} - M_{pay} - nM_{su} - nM_{sd} - M_{res}}{1 + a + (\lambda I_s/T)} \tag{6}$$

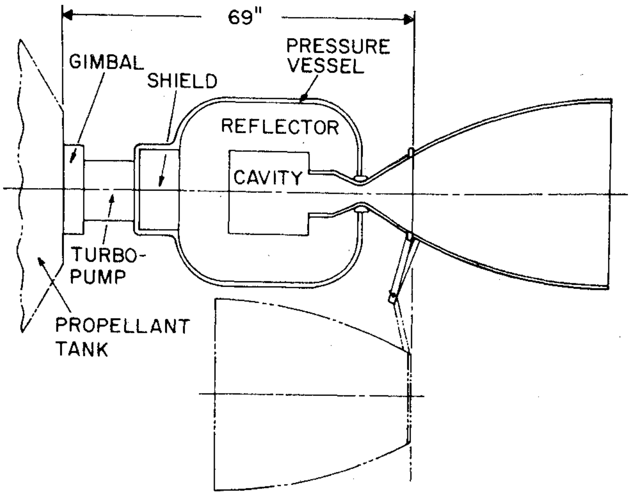

Fig. 1 CCNR preliminary layout.

Since this analysis is directed toward orbit-to-orbit shuttle missions, the variables in Eqs. (5) and (6) must be selected within shuttle launch capabilities. Baseline vehicle estimates[6] indicate that the earth-to-orbit vehicle is capable of boosting approximately 65,000 lb into 235 naut mile circular orbit due east from Cape Kennedy (i.e., the orbit is inclined at 23.5°). This restriction represents a structural design limit. However, it may readily be shown that the volume of the shuttle's 60 ft long by 15-ft-diam payload bay limits the amount of low-density propellant to be carried rather than vehicle gross weight. A preliminary layout of an advanced OOS using the CCNR engine is shown in Fig. 1. Sixteen feet of the interior bay length are allocated for OOS payload volume. The engine depicted utilizes a 10 in. reflector with a folded nozzle skirt similar to that employed in Ref. 7. Nominal vehicle characteristics are shown in Table 1. It is possible to vary parametrically a number of these characteristics and study the effects of the variation on ideal velocity capability as a function of payload. The following parameters have been selected to be varied.

a) Figure 2a is a plot of vehicle performance for changes in specific impulse while other parameters including total vehicle weight are held constant. As one would expect, vehicle performance is sensitive to specific impulse. The ideal velocity is increased by 10% for a like change in specific impulse.

b) Figure 2b demonstrates the effect of fuel loss rate upon performance. Increasing the loss rate to ten times that predicted in the early reactor engineering study[4] is roughly equivalent to a 100 sec drop in specifice impulse.

c) Increasing the tankage fraction from a nominal 5% value to a 10% allowance (to account for extensive baffles and thermal protection) is roughly equivalent to a 100 sec drop in specific impulse. The result of this variation is indicated in Fig. 3a.

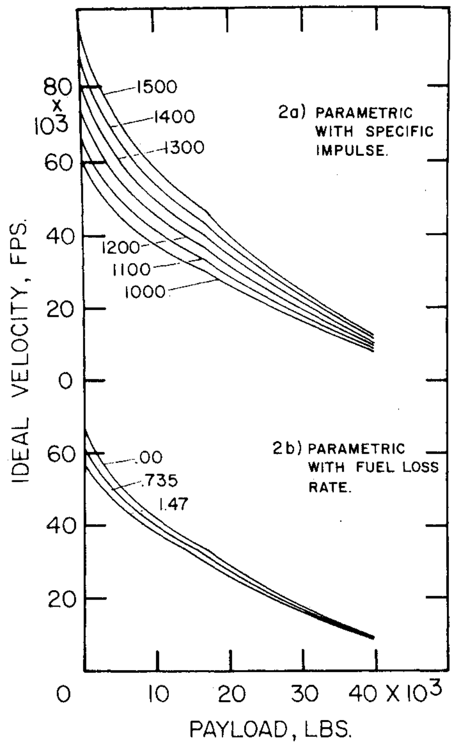

Fig. 2 Effect of variable specific impulse and furl loss rate.

d) The effects of varying engine thrust-to-weight ratio are shown in Fig. 3b. Variation by a value of one in either direction from the predicted value of five is roughly equivalent to a 30 sec variation in specific impulse for the general range of payloads which will be of interest (~10,000 lb). It is interesting to note that a further increase of the thrust-to-weight ratio from six to eight is only equivalent to a gain of approximately 50 sec more specific impulse.

e) Figure 4a does not demonstrate the critical effect that the value of the shield constant may have on performance. The shielding required depends on the mission application (i.e., whether the vehicle is manned or unmanned and whether shadow or 4π shielding is employed). Since a calculation of vehicle shielding requirements is beyond the scope of this study, a value of 200 psf has been selected somewhat arbitrarily as representative for unmanned missions. This value is consistent with those utilized in Ref. 7 when one accounts for a higher neutron flux density that is expected in the CCNR concept. This selection is equivalent to a 380 lb shield weight allowance for the nominal reference design engine. It should be noted that considerably larger shields may be required for manned applications. When this is the case, a significant degradation in performance may be seen.

Table 1 Comparative OOS vehicle characteristics

	O_2/H_2 chemical	Small solid core reactor	Pessimistic CCNR	Nominal CCNR	Optimistic CCNR	Growth potential
Specific impulse	456	860	1050	1100	1200	1500
Thrust	20,000	16,135	20,000	20,000	20,000	20,000
Fuel loss rate	N/A	0	0.147	0.147	0.147	0
Initial propellant	58,337	30,441	34,500	34,500	34,500	34,500
Tankage fraction	0.0305	0.052	0.052	0.052	0.052	0.052
Engine weight	488	5103	3960	3311	3311	3311
Shield diameter	N/A	2.116	1.378	1.378	1.378	1.378
Shield constant	0	118	200	200	200	200
Structural weight	4503	2596	2596	2596	2596	2596
Start up/shutdown	2.176	33	2.77	2.77	2.77	2.77

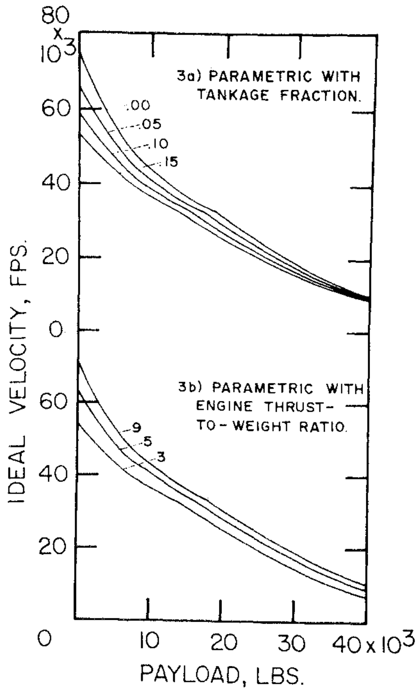

Fig. 3 Effect of variable tankage fraction and engine thrust-to-weight ratio.

f) The sensitivity of performance to shield diameter is illustrated in Fig. 4b. Diameter is varied by 300% from the 1.378 ft value of the reference design. The comments from the preceding paragraph are also applicable here, especially where dense shields of a larger diameter are to be employed.

g) Finally, the amount of nuclear fuel required was varied between zero and ten times the value estimated as necessary.[4] The mass fraction of fuel is small and no effect is apparent. However, it is interesting to note that no accounting has been made for changes in engine thrust-to-weight ratio which may occur because of lower uranium concentrations in the cavity. It is conceivable that such lower concentrations may be effectively employed to alter fuel vaporization losses, without significantly changing vehicle performance.

In addition to estimating the nominal characteristics of the CCNR vehicle, it is possible to make optimistic and pessimistic estimates of these values. Such a procedure is wise in light of the engineering uncertainty of an unproven concept. The basis for these judgements was that pessimistic values should have a very high probability of being achieved, while optimistic values would require a state-of-the-art advancement. It was somewhat arbitrarily decided that the nominal prediction of fuel vaporization loss rate could not be exceeded for reasons of economy and space poisoning. Therefore the pessimistic specific impulse was dropped by 50 sec to correspond with a lower operating temperature which might be required to control vaporization. The pessimistic engine also suffers a 20% weight penalty. The optimistic engine is capable of operating at an increased temperature (corresponding to a 1200 sec specific impulse) because of an assumed breakthrough in fuel technology where vaporization losses do not increase. Finally an attempt was made to estimate the growth potential of the CCNR concept. This estimate is based upon the assumption that a vaporized fuel condensation cycle may be added without an over-all weight penalty. While such an assumption is indeed ambitious, it serves the purpose of placing an upper bound on expected performance. Such a cycle would allow operation at 1500 sec specific impulse. A summary of values selected is listed in Table 1 along with those for comparative chemical and small solid core nuclear systems.[7–10]

The open cycle gas core reactor and nuclear light bulb concepts were examined for the thrust levels of interest. These concepts were found to be at a severe disadvantage because of their relatively large size and weights at such low-thrust levels; they are not considered further. Those concepts considered are compared in Fig. 5. It should be noted that even pessimistic CCNR estimates show a considerable performance increase over the small solid core nuclear engine. Confidence in the optimistic and pessimistic estimates is obtained through the fact that data from the original engineering study[4] falls within these bounds.

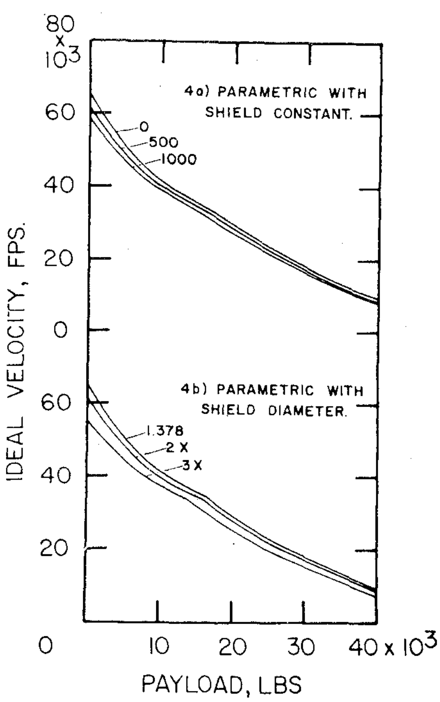

Fig. 4 Effect of shielding parameters.

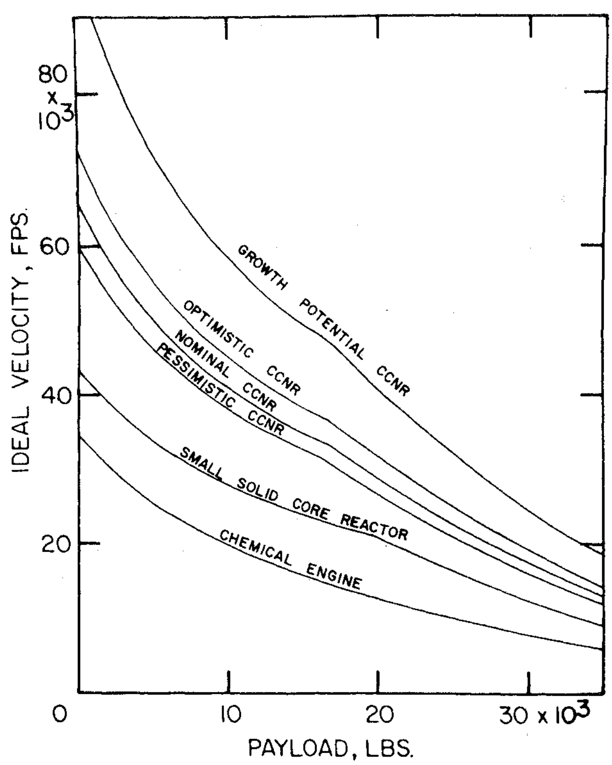

Fig. 5 Concept performance comparison.

Mission Performance Simulation

Based upon the Space Shuttle projections, numerous OOS mission models were developed and evaluated. Impulsive multiple burns were assumed with their velocity increments representing the class of missions of interest. The missions fell into three categories: transfer between low altitude (100 naut miles and 300 naut miles) orbits, transfer between a 100 naut miles parking orbit and geosynchronous orbit, and missions requiring large rapid orbital plane changes. The missions were simulated with deployed, retrieved, and exchanged payloads. The simulation was simplified by neglecting propellant boiloff during the mission; however, some consideration of this matter has been made in determining the thermal and structural requirements of the tankage fraction. Furthermore, an allowance has been made for reduced impulse during the engine startup and shutdown cycles for the multiple burn trajectories. In all cases, a passive rendezvous was assumed.

In order to conform to the volume limitations of the EOS payload bay, initial propellant values were those shown in Table 1. If gross weight was exceeded, the propellant tank was appropriately resized. This decision was made in keeping with the reusable vehicle philosophy of the Space Transportation System. However, such a decision does not preclude further growth potential of the CCNR concept through the use of strap-on external propellant modules. A result of this analysis was the demonstration that the selected missions could be performed within the volume constraints of the internal bay.

A typical result of mission simulations is displayed in Fig. 6. Excess velocity available at the end of the mission is calculated as a function of OOS payload. Propellant reserves are not considered, but can readily be subtracted from the excess velocity available. Mission growth potential available with the CCNR is demonstrated by selecting a desired operating point on the graph. System capabilities that are above the operating point represent the ability to perform the mission along a higher energy transfer path in those cases where vehicle reaction time is critical. By the same token, capabilities which lie to the right of the operating point represent an ability to carry increased payloads.

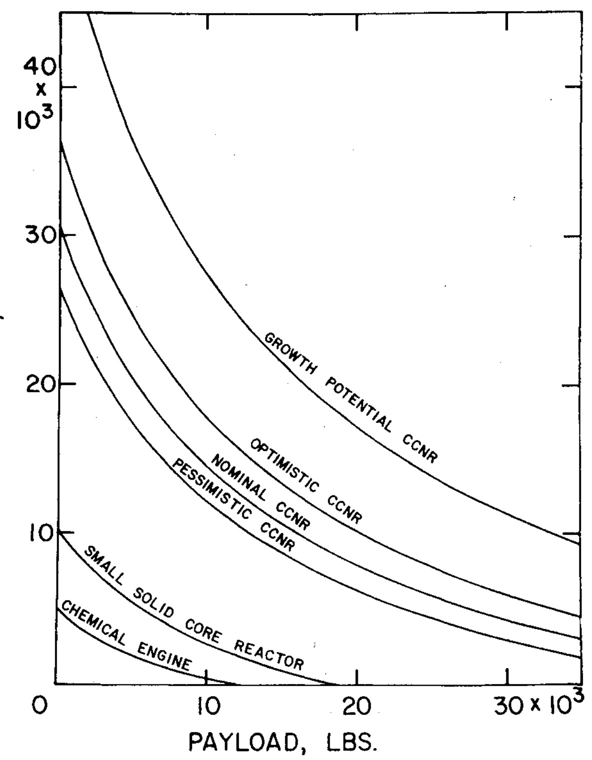

Fig. 6 Simulation of payload deployment to synchroneous orbit.

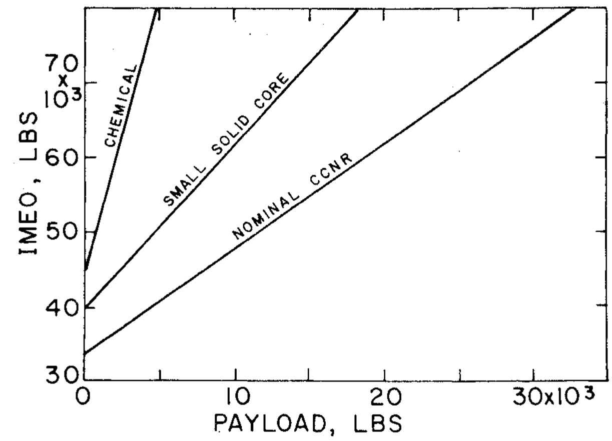

Fig. 7 Cost indications for round trip deployment and retrieval to synchronous orbit.

The initial mass which must be placed in Earth orbit (IMEO) to perform a given mission may be used as a qualitative measure of concept operational costs. It should be pointed out that such operational costs do not include research and development. An example of initial boost requirements as a function of payload is shown in Fig. 7. Similar calculations for other missions were performed with similar results.

Conclusions

Based upon performance potential, the Colloid Core Reactor concept appears to be a viable option for development as an operational system. Rapid application to an advanced Space Shuttle appeared feasable. For high-energy shuttle missions, requiring the use of an upper stage, the concept provides the possibility for considerable mission growth, either in terms of rapid response times or increased payload capability. For certain classes of missions, namely those with large energy requirements such as rapid large change in orbital plane, the CCNR was the only concept of those examined found able to perform the mission. Such advanced missions could be performed with current state-of-the-art launch hardware and remain within the shuttle philosophy of a reusable system. As further incentive for concept development, indications are that the CCNR concept would perform advanced missions at a reduced operating cost.

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Half- and Full-Model Experiments on Slender Cones at Angle of Attack

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An evaluation has been made of the angle-of-attack range at which experiments on slender sharp cones can be performed using half models. The evaluation was based partly on a comparison of surface flow patterns over full and half models, partly on the measurement of the static side force on full models at zero yaw, and partly on a comparison of oscillatory pitching results obtained with full and half models. Most of the results were obtained at a Mach number of two in the range of angle of attack between 0° and 30°, but the static side force was also measured at Mach numbers between 0.5 and 0.8. In all cases investigated it was found that up to an angle of attack of at least 15° no significant side force could be detected on full models, and that the pitch damping results and the surface flow patterns (with the exception of the primary attachment line) obtained on full and half models were in close agreement. The half-model technique appears therefore suitable for oscillatory experiments on slender cones (and probably on other similar geometries) at angles of attack at least up to 15°, at low supersonic speeds. Application to higher speeds, however, may very well require special corrections for tunnel-wall or reflection-plate boundary layer.

Nomenclature

C_m = (pitching moment)/(qSl)
$C_{m\theta}$ = $\partial C_m/\partial\theta$, static pitching moment derivative
$C_{m\dot{\theta}}$ = $\partial C_m/\partial(l\dot{\theta}/2V)$, pitch damping derivative
C_N = (normal force)/(qS)
$C_{N\theta}$ = $\partial C_N/\partial\theta$
$C_{N\dot{\theta}}$ = $\partial C_N/\partial(l\dot{\theta}/2V)$
C_Y = (side force)/(qS)
k = $\pi\nu l/V$, reduced frequency
l = model length
q = freestream dynamic pressure
S = base area of the model
V = freestream velocity
x_0 = distance of axis of oscillation from cone apex
α = (mean) angle of attack
$\theta, \dot{\theta}$ = angle of oscillation in pitch about a fixed axis, and its first derivative with respect to time
θ_c = cone semiangle
ν = oscillation frequency

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Introduction

FOR some wind-tunnel experiments the presence of a sting at the rear of a model may constitute a source of significant error. Alternative techniques to the conventional sting support are therefore of interest. One such technique involves the use of half models. Its application to oscillatory experiments at zero or low angles of attack (5°) was recently discussed by two of the present authors.[1,2] Since the interest in oscillatory experiments at higher angles of attack is rapidly increasing, an investigation was undertaken to determine the range of angle of attack in which this technique may be expected to give satisfactory results. Since any half-model technique can only be used when the flowfield is symmetric and similar to that on a corresponding full model, an examination of these aspects of the flow constituted an important part of the investigation. It consisted partly of measurements of the static side forces on full models at zero yaw and partly of a surface-flow visualization study on both full and half models. As a result, it was possible to determine the highest angle of attack at which the flow over a full, unyawed model still was symmetrical and at which the patterns of the flow-separation and flow-reattachment lines on full and half models still were in good agreement. The investigation was concluded with a series of oscillatory experiments using both full and half models, from which the static and dynamic pitching moment derivatives were determined. Most of the work was performed at a Mach number of 2 at angles of attack ranging from 0° to 30°, but the static side-force measurements were carried