N71-31246

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COMPARATIVE PERFORMANCE OF NUCLEAR AND CRYOGENIC CHEMICAL SPACE PROPULSION SYSTEMS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1971

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-2352		

4. Title and Subtitle	5. Report Date
COMPARATIVE PERFORMANCE OF NUCLEAR AND CRYOGENIC CHEMICAL SPACE PROPULSION SYSTEMS	August 1971
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Duane W. Dugan	A-3812
	10. Work Unit No.
9. Performing Organization Name and Address	130-06-16-05-00-15
Office of Advanced Research and Technology Advanced Concepts and Missions Division Moffett Field, Calif., 94035	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D. C., 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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Both single stages and two tandem stages of propulsion are considered. Boundaries are generally defined on the basis of sizing propulsion systems for each requirement of initial mass and velocity change, but the effects of fixing the stages at one size or another is also assessed. The use of a fixed-size nuclear engine (thrust of 75,000 lbf and mass of 25,000 lbm) is included for comparison. Because the stage inert masses do not include mission-dependent items such as meteoroid and thermal protection for propellant tanks, and cool-down propellants in the case of the nuclear system, the boundaries obtained represent lower bounds. The effects of including additional radiation shielding in the nuclear stage for manned applications, however, are shown parametrically, as are the effects of a ±10 percent variation about the nominal inert masses of the nuclear system. Also investigated are the effects of specifying that the performance of the nuclear system be greater than that of the chemical system by given factors.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Solid-core nuclear space propulsion Chemical space propulsion	Unclassified – Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	15	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

NOMENCLATURE

A	advantage factor, ratio of payload of nuclear system to that of chemical system for equal initial gross mass
emos	unit of speed equal to Earth mean orbital speed, 29.785 km/s
g_O	gravitational constant
I_{sp}	specific impulse
M_E	engine mass
M_F	mass of inerts that do not vary appreciably with propellant mass
M_L	payload mass
M_O	value of M_S at $M_P = 0$
M_P	propellant mass
M_P'	slope of curve of M_S versus M_P
M_S	inert mass of propellant module
M_i	initial gross mass
T_N	thrust level of nuclear stage
T_c	thrust level of chemical stage
V_∞	hyperbolic excess speed
ΔV	velocity increment

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SUMMARY

Solid-core nuclear and cryogenic (LH_2/LOX) propulsion systems are compared in a generalized way in order to locate boundaries of initial gross mass in Earth orbit and of payload mass that will define the region of performance superiority of one system over the other. The orbit from which both propulsion systems are considered to inject their respective payloads is assumed to be circular at an altitude of 150 nautical miles. The specific impulse of chemical stages is taken to be 456 seconds and that of the nuclear stages is assumed to have a nominal value of 825 seconds, a lower value of 800 seconds, and a high value of 850 seconds. Boundaries of equal performance are defined as a function of velocity increment for near-Earth orbital maneuvers for which gravity losses are negligible, and as a function of hyperbolic excess speed for Earth-escape missions in which gravity losses are taken into account.

Both single stages and two tandem stages of propulsion are considered. Boundaries are generally defined on the basis of sizing propulsion systems for each requirement of initial mass and velocity change, but the effects of fixing the stages at one size or another is also assessed. The use of a fixed-size nuclear engine (thrust of 75,000 lbf and mass of 25,000 lbm) is included for comparison. Because the stage inert masses do not include mission-dependent items such as meteoroid and thermal protection for propellant tanks, and cool-down propellants in the case of the nuclear system, the boundaries obtained represent lower bounds. The effects of including additional radiation shielding in the nuclear stage for manned applications, however, are shown parametrically, as are the effects of a ±10 percent variation about the nominal inert masses of the nuclear system. Also investigated are the effects of specifying that the performance of the nuclear system be greater than that of the chemical system by given factors.

INTRODUCTION

An earlier work (ref. 1) compared single-stage chemical and nuclear propulsion systems in their application to Earth-escape missions. In this work, the mass of the nuclear engine used was unrealistically low compared with more recent estimates for the long-life, multiple-restart version of Nerva-type engines. Likewise, inert masses for chemical systems were assumed to be a constant fraction of the mass of usable propellants, and gravity losses were not taken into account. Reference 2 compared the performance of small water-graphite nuclear rocket stages with that of specific operational and conceptual chemical stages for nonmanned missions. The nuclear rocket

RESULTS AND DISCUSSION

Several criteria are used to obtain boundaries between the regions of superior performance of nuclear and chemical propulsion systems. In addition to differentiating between the use of propulsion systems for near-Earth orbital maneuvers and for Earth-escape maneuvers as previously discussed, several other ways of establishing such boundary curves are considered. These include comparing single-stage performances, the performance of two-stage chemical with that of both single-stage nuclear and nuclear/chemical two-stage propulsion systems, and specifying that a nuclear stage have payloads larger by a factor A than a chemical stage for equal initial masses. Also, the effects of a ±10 percent variation in the inerts and a ±25 s variation in the specific impulse of the nuclear stage on the boundary are included. The effects of fixing the thrust level and mass of the nuclear rocket engine are also examined. One final task is to show the effects on the boundary due to fixing the inerts of both chemical and nuclear stages at one or another level, which is equivalent to using for all requirements propulsion stages with propellant capacities and thrust levels found optimum for one or another combination of payload and ΔV requirement. Boundary curves obtained on the foregoing bases are discussed in the following sections.

Equal-Performance Boundaries

Single-stage chemical and single-stage nuclear propulsion systems– From such plots as shown in figure 1, or from a computerized algorithm, values of equal payload and of corresponding equal initial mass are used to define equal-performance boundaries as a function of ΔV or of V_∞. The stage mass can be obtained as the difference between the initial mass and payload mass. Figure 2 shows the boundary curves for equal payload and initial mass for single-stage chemical and nuclear systems assumed to be used in near-Earth orbital maneuvers. As noted in appendix A, the thrust-to-weight ratios that provide essentially maximum performances and at the same time reduce gravity losses to negligible quantities in these maneuvers are 0.2 for the nuclear systems defined here and 0.4 for chemical systems with a specific impulse of 456. The boundary curves of figure 2 illustrate clearly that nuclear systems are most appropriate for large-payload, high-energy (large ΔV) missions. This is a result of the relatively high inert fraction (compared with that of chemical systems) of the nuclear system for the smaller stage masses. For nonmanned cargoes (no additional shielding for nuclear engines) the minimum initial gross mass is approximately 114,000 lbm (51,700 kg) and the payload for this initial mass is about 31,000 lbm (14,000 kg). For manned applications, the boundary curves lie significantly higher than

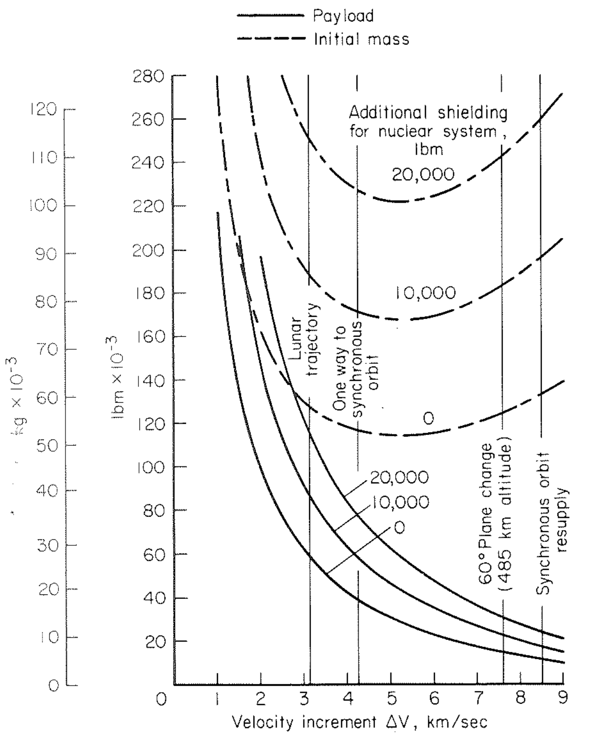


Figure 2.– Equal-performance boundaries for single-stage nuclear and chemical systems for near-Earth orbital maneuvers.

those for nonmanned cargoes. The minimum initial masses increase by about 5,400 lbm for each 1,000 lbm of additional shielding required in the nuclear stages, and the corresponding payloads must be about 1,500 lbm greater for each 1,000 lbm of shielding to achieve comparable performance with chemical stages.

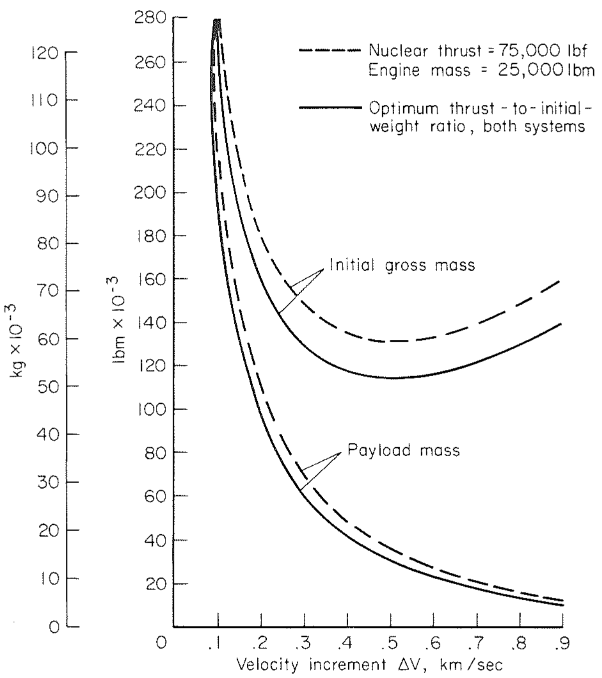


Figure 3.– Effects of fixing thrust level and mass of nuclear engine on equal-performance boundaries for single stages (near-Earth orbital maneuvers).

The effects of fixing the nuclear engine size on the equal-performance boundaries for nonmanned near-Earth applications are shown in figure 3. Here the thrust level of the nuclear stage is assumed to be 75,000 lbf, and the engine mass is taken as 25,000 lbm (see appendix A). The initial-mass boundary for the fixed nuclear size is about 15 percent higher than for the case in which the thrust of the nuclear engine is varied with initial mass to maintain a given ratio of thrust to weight, and the payload boundary is also higher by about 15 percent. The 75,000-lbf engine is clearly too large for near-Earth orbital maneuvers and thus suffers some loss in performance compared with that of smaller engines (thrust levels of about 22,000 lbf to 50,000 lbf).

Figure 4 presents similar curves for the use of the two propulsion systems for Earth-escape maneuvers. An auxiliary scale on the abscissa relates the impulsive ΔV to the V_∞ to facilitate comparison with figure 2. The effects of the larger gravity losses of a nuclear stage compared with those of a chemical stage (both using essentially optimum thrust levels) are evidenced by the increase in both the initial gross mass and corresponding payload required to make the nuclear stage competitive with the chemical when compared with results from figure 2. In figure 2, it is noted that the minimum for the initial mass occurs at about 5.2 km/s, which corresponds to a V_∞ of 0.22 emos (6.55 km/s) if gravity losses are neglected. The V_∞ associated with the mimimum initial mass in figure 4 is 0.20 emos. However, the total ΔV for this maneuver, including gravity losses, is about 5.165 km/s for the nuclear stage, and 4.784 km/s for the chemical stage. As the required V_∞ is increased, the gravity losses, and hence total ΔV of the nuclear stage increase more rapidly than those of the chemical stage. For example, at a V_∞ of 0.40 emos, the total ΔV are 8.97 and 8.66 km/s for the nuclear and chemical systems, respectively, as compared with an impulsive ΔV of 8.44 km/s.

Figure 4 may be used to evaluate the appropriateness of one stage or the other for various interplanetary missions. For example, for a mission to Jupiter ($V_\infty \approx 0.3$ for 800-day trip time) it can be seen that from a performance standpoint, payloads less than about 25,000 lbm (11,340 kg) are more suited to chemical stages. For payloads larger than about 7,500 lbm (3,400 kg) injected to flyby or to orbit Uranus in the relatively short trip time (compared with the Hohmann trip time) of 1,800 days ($V_\infty \approx 0.47$ emos), the nuclear stage would be preferable. Note that the initial-mass

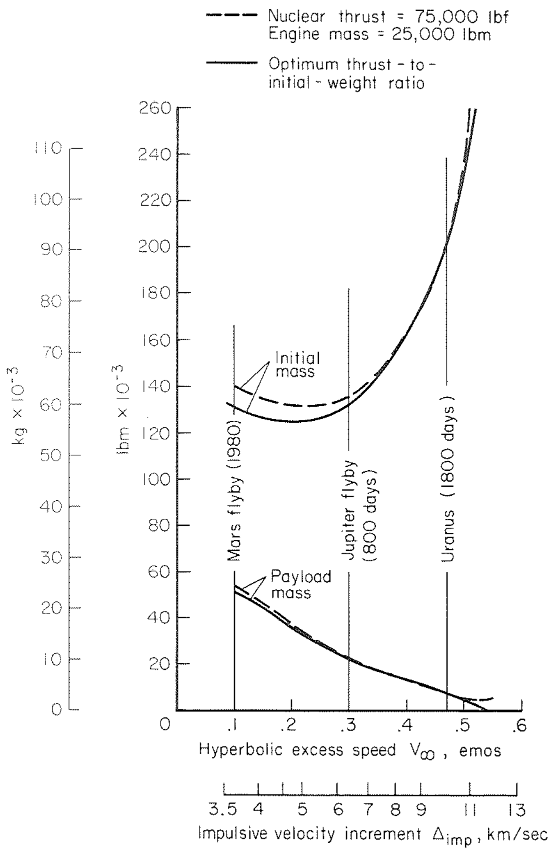


Figure 4.– Equal-performance boundaries for single-stage nuclear and chemical systems – Earth-escape missions.

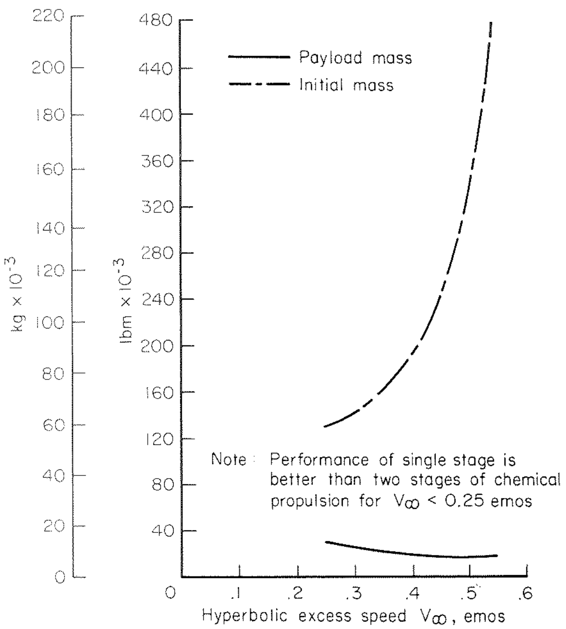


Figure 5.– Equal-performance boundaries for single-stage nuclear systems and two-stage chemical systems for nonmanned Earth-escape missions.

requirement for a payload of 7,500 lbm for missions of this energy is nearly 205,000 lbm (93,000 kg), and therefore it would be almost imperative to reduce the size of the launch vehicle required for such high-energy missions by employing space propulsion systems of higher performance than that of either single-stage chemical or nuclear systems. Also shown in figure 4 for comparison are the initial-mass and payload boundary curves obtained by assuming the thrust level of the nuclear system to be fixed at 75,000 lbf. At the lower V_∞, the engine is larger than necessary to offset the effects of gravity losses (i.e., the thrust-to-weight ratio is too high). At larger values of V_∞, however, the initial-mass requirements are large enough to make the 75,000-lbf thrust level more nearly optimum, and the differences between the boundary curves tend to disappear as shown. For V_∞ larger than about 0.5 emos, the initial-mass requirements become so large that the initial acceleration of the nuclear stage is reduced far below the optimum value and gravity losses seriously degrade performance.

Two-stage chemical and single-stage nuclear propulsion systems– It is common practice to design chemical systems of more than one stage. For this reason, a comparison between two chemical stages in tandem and a single nuclear stage is of interest. It is assumed that identical engines are used in both stages. The performance boundaries for such a comparison are shown in figure 5 for the Earth-escape maneuvers (nonmanned applications only).

For hyperbolic excess speeds less than about 0.25 emos (7.45 km/s), staging of chemical systems is not advantageous, so that the curves of figure 4 are appropriate up to that point. Beyond a value of $V_\infty \approx 0.3$, the curves of figure 5 differ markedly from those of figure 4 for single stages. Note the change of scale between the two figures. The boundary curves indicate that the two-stage chemical system is superior to the nuclear system over the entire range of V_∞ studied for payloads less than about 16,000 lbm (7,260 kg). The mass of the nuclear stage that is required to make nuclear propulsion competitive with chemical propulsion is considerably larger, particularly at the higher values of V_∞, when two chemical stages rather than one are used to define the boundaries of superiority. Comparison of figures 4 and 5 also shows the improvement in performance that accompanies increasing size of the nuclear stage. Whereas in the second example cited above, a payload of only approximately 7,500 lbm at an initial mass of about 205,000 lbm could be injected to a V_∞ of 0.47 (payload ratio of nearly 0.037) by the nuclear stage; figure 5 indicates that about 16,000 lbm of payload would require about 265,000 lbm of initial mass (payload ratio of 0.06). An equal increase in performance, of course, is achieved by the chemical system chiefly through the addition of another stage.

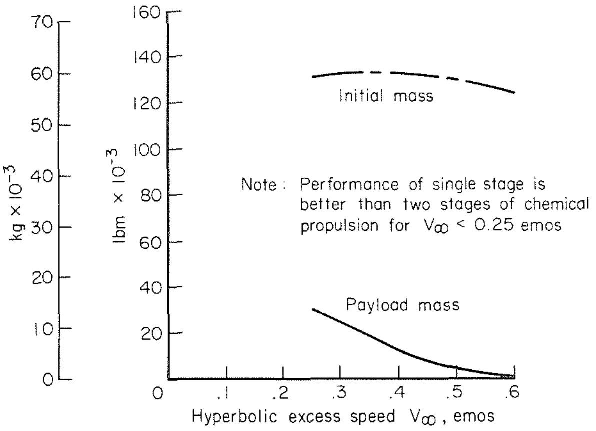


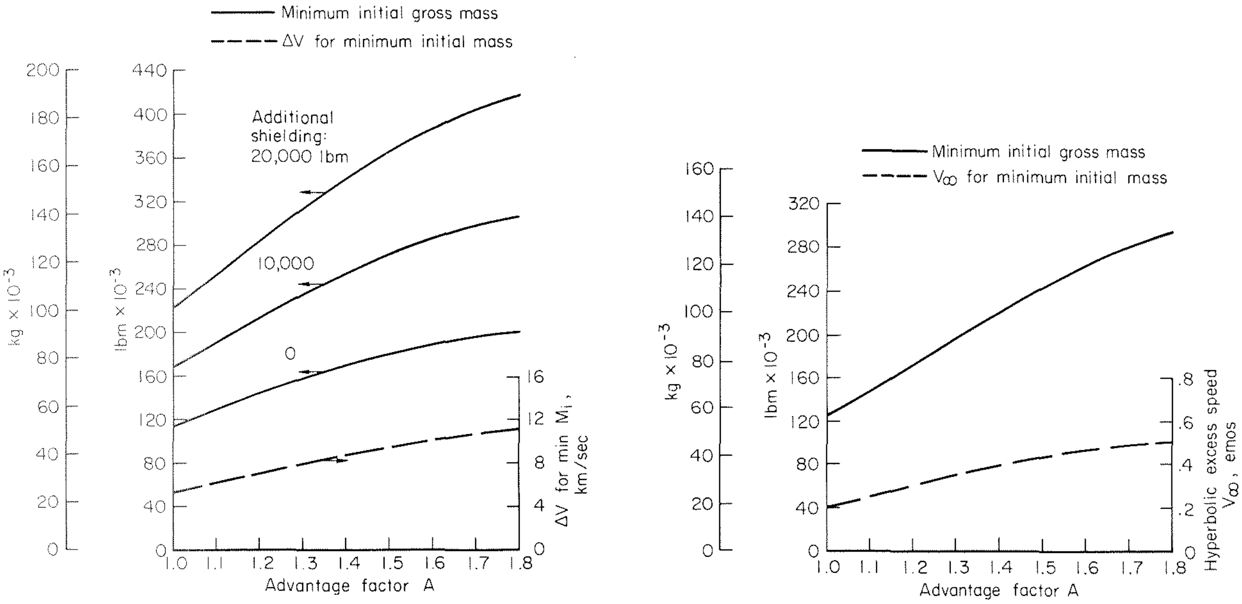
Figure 6.– Equal-performance boundaries for two-stage nuclear-plus-chemical systems and two-stage chemical systems for Earth-escape missions.

Two-stage chemical and nuclear plus chemical upper stage– If both nuclear and chemical stages were available, a logical method of staging would be to combine chemical and nuclear stages in a mixed propulsion system. As noted in reference 3, better performance results when the chemical system is used as a second rather than a first stage. Figure 6 compares the performance of the mixed stages with that of two chemical stages in Earth-escape maneuvers.

Here again, the use of more than one stage of chemical propulsion does not offer performance advantages below a V_∞ of about 0.25 emos. The addition of a chemical stage to a nuclear stage markedly increases the region of superiority of the mixed stages at the expense of the two chemical stages (cf. figs. 5 and 6, observing the different scales for mass). If the Uranus mission cited as an example earlier is used here, a payload as small as 6,500 lbm could be injected for an initial mass in Earth orbit of about 130,000 lbm. The payload fraction in this case is 0.05. The nuclear/chemical system would benefit more in performance from an increase in the initial mass than would the two chemical stages.

Performance-Advantage Bias

It may be of interest for economic or other reasons to define the performance boundary for nuclear systems that have a specified higher payload performance than chemical systems for equal initial gross masses. Under such a condition, the region of applicability of chemical systems would, of course, be larger than for equal performance. The effect of requiring a performance advantage from 1.0 to as much as 1.8 for a single-stage nuclear over a single-stage chemical propulsion system used for near-Earth orbital maneuvers is shown in figure 7(a) and for Earth-escape maneuvers in figure 7(b). Instead of entire boundary curves, figure 7 shows the variation of the minimum initial mass and corresponding ΔV or V_∞ over a range of advantage factors A. The figure shows a significant increase with A in both the minimum initial mass and the corresponding ΔV or V_∞ at which the nuclear system can compete in performance with the chemical system under the specified



(a) Near-Earth orbital maneuvers.

(b) Earth-escape missions.

Figure 7.– Variation of minimum initial gross mass and associated energy with advantage factor for single-stage nuclear and chemical systems.

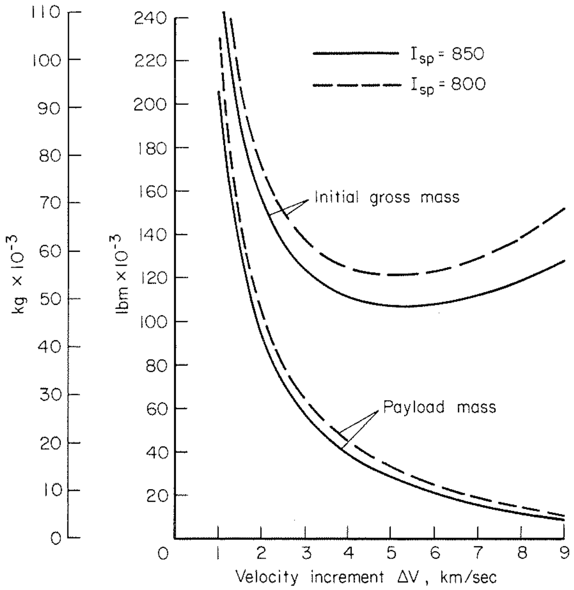
constraint. As an example, if instead of requiring that the performance of the two systems be equal (A = 1), it is stipulated that the nuclear system shall have 50 percent greater performance than the chemical (A = 1.5), the minimum initial mass boundary would increase from 114,000 lbm (51,700 kg) to 180,000 lbm (81,650 kg), and the corresponding ΔV would increase from 5.2 km/s to 9.4 km/s in the case of near-Earth orbital maneuvers and nonhuman cargoes. If shielding is required for manned applications of the nuclear system, the penalty in additional initial-mass requirements increases from 5,800 lbm at A = 1.0 to 9,200 lbm at A = 1.5 for each 1,000 lbm of additional shielding. The velocity increment at which the minimum initial mass occurs is not affected by the addition of shielding to the nuclear system. Corresponding increases for nonmanned Earth-escape applications are an initial-mass rise from 125,000 lbm (56,700 kg) at A = 1 to 244,000 lbm (110,680 kg) at A = 1.5, and a V_∞ increase from 0.20 to 0.43 emos.

Effect of Variations in Performance Parameters

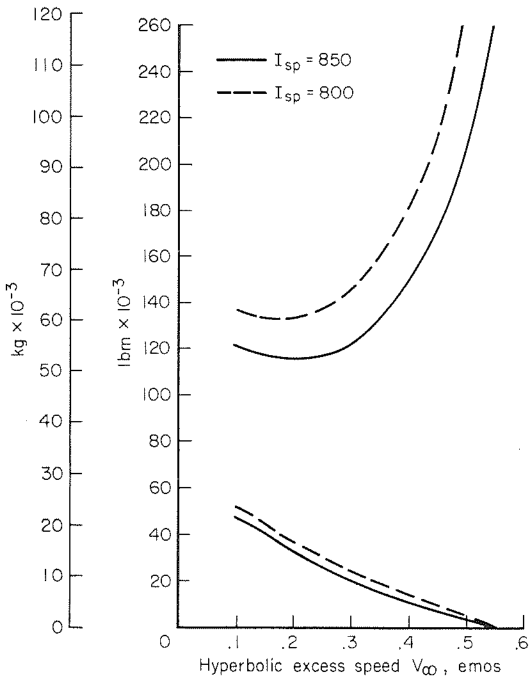
The boundary curves presented in the previous sections are valid only for the nominal performance parameters and scaling laws listed in appendix A (except where noted as in the case of the fixed-size nuclear engine). In view of the uncertainties that can exist in performance parameters, it is appropriate to examine the effect of variations in these parameters on the boundary curves.

In the case of chemical systems, the nominal scaling laws for propellant-module inert mass and for rocket engines adopted in this study yield values that are in close agreement with those of existing upper stages. Similarly, the assumed specific impulse of 456 s is within the range projected for chemical systems. Thus, since the major uncertainties are those associated with the nuclear system parameters, variations of only the latter are considered here.

The effects of a ±25-s variation in the assumed nominal nuclear specific impulse of 825 s on the equal performance curves for single-stage systems are shown in figure 8. The results indicate that this variation does not represent a significant perturbation on the nominal boundary curves shown in figure 2.



(a) Near-Earth orbital maneuvers.

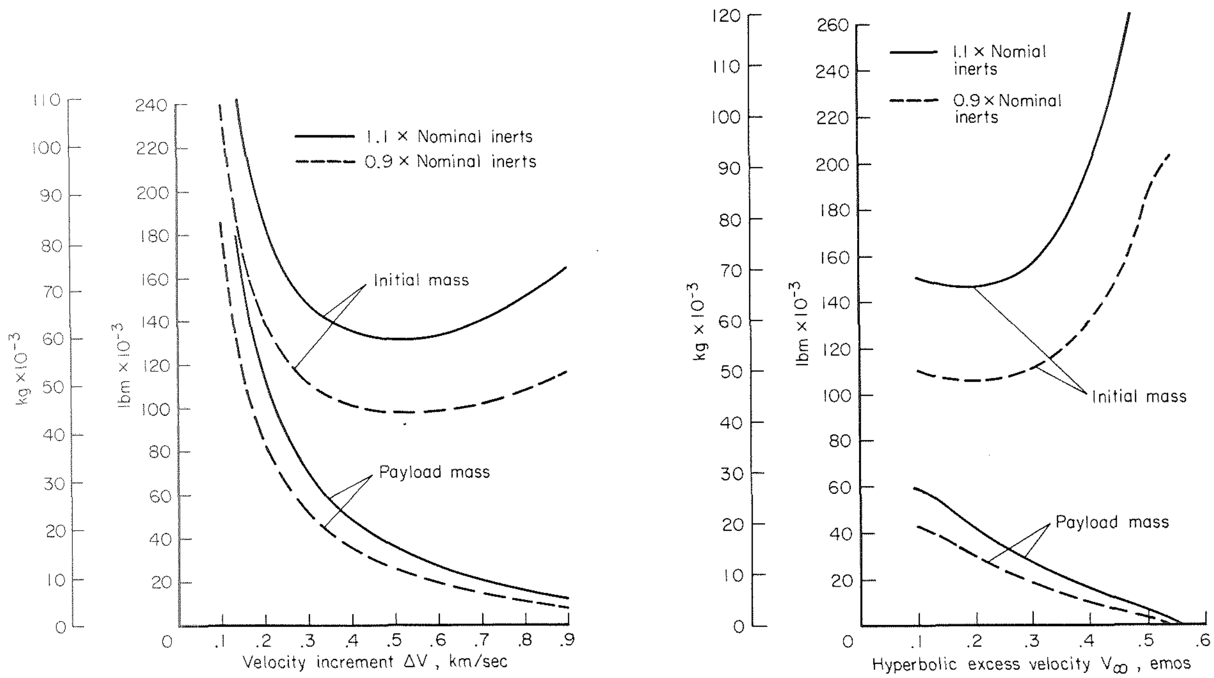


(b) Earth-escape missions.

Figure 8.– Effects of ±25-s variation in specific impulse of nuclear stage on equal-performance boundaries for single-stage nuclear and chemical systems.

The effects of a ±10-percent variation in the total nuclear stage inert weights (engine plus tankage) on the boundary curves for single-stage systems are shown in figure 9. In the neighborhood of minimum initial mass, the boundary curves for initial mass and payload vary by about 15 and 18 percent, respectively, for near-Earth maneuvers, and by about 17 and 15 percent, respectively, for Earth-escape maneuvers compared with those obtained on the basis of nominal nuclear stage inerts. This variation represents a significant perturbation and suggests that larger uncertainties in nuclear stage inert weights could significantly affect minimum competitive nuclear stage sizes.

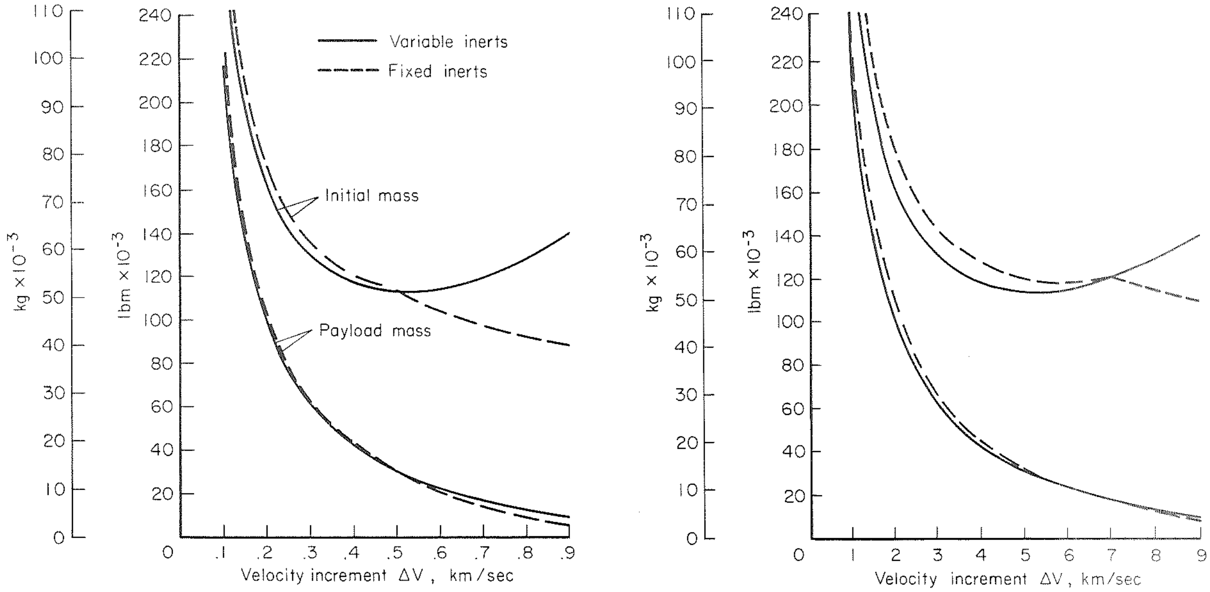
The boundary curves presented in the earlier sections are based on scaled inerts. In actual cases, the inerts may be fixed. "Fixed" inerts are representative of those used in specific stages; that is, the propellant loading is varied within the limits of a fixed-capacity tank, and engine weight is constant. To investigate the effects of fixed stage size on performance boundaries, the assumption is made that both propulsion systems are each designed for a common specific payload and a specified velocity; two examples are given for near-Earth orbital maneuvers in figure 10. The variation in the performance boundaries between fixed and scaled inerts is shown in the figure for single-stage systems. The results show that this assumption does not have a significant effect on the boundary curves except at ΔV's beyond those at which the propellant capacities of the stages are reached. The boundary curve for initial mass decreases rather than increases with ΔV beyond the design ΔV because without additional propellant, an increase in ΔV must be obtained by decreasing the mass to be accelerated. This decrease is obtained by reducing the mass of the payload to values lower than the design value. Because of its higher specific impulse, the nuclear system is more efficient than the chemical in accommodating ΔV larger than that chosen for design of the stage.



(a) Near-Earth orbital maneuvers.

(b) Near-Earth orbital maneuvers.

Figure 9.– Effects of a ±10-percent variation in inert mass of nuclear stage on equal-performance boundaries of single-stage nuclear and chemical systems.



(a) Both systems designed for 30,500-lbm payload; $\Delta V = 5$ km/s.

(b) Both systems designed for 17,300-lbm payload; $\Delta V = 7$ km/s.

Figure 10.– Effects of fixing inerts of both chemicalsand nuclear single stages on equal-performance boundaries; near-Earth orbital maneuvers.

It might be noted that for nuclear systems the thrust levels lying just on the single-stage boundary curves shown in this paper are of the order of only 20,000 to 50,000 lbf for near-Earth orbital maneuvers ($T/W_i = 0.2$). For Earth-escape maneuvers, however, nuclear-engine thrust levels lie between about 50,000 lbf for minimum initial mass and approximately 104,000 lbf for vanishing payload at $V_\infty = 5.2$ emos ($T/W_i = 0.4$). For an advantage factor of 1.5, the nuclear thrust level would be no less than about 98,000 lbf.

CONCLUSIONS

The conclusions outlined here are based on the nominal performance parameters and scaling laws listed in appendix A. Also, since such mission-dependent inert masses as meteoroid and thermal protection and possible propellant boiloff are not included in the results presented, the performances given here are somewhat optimistic and the performance boundary curves presented should be regarded as lower bounds. Any judgment of the preferability of one or the other system, of course, depends on the payload and energy requirements of given missions, and should include economic considerations. No attempt to make such judgments is made here.

1. The smallest initial mass for which a nuclear system is competitive with single-stage chemical systems is about 114,000 lbm (51,700 kg) for near-Earth orbital maneuvers for nonmanned applications, and about 5,400 lbm (2,450 kg) larger than this figure for each 1,000 lbm (454 kg) of additional shielding required by the nuclear stage in manned applications. If a significant performance advantage as large as 1.5 is required for the nuclear system, this minimum initial mass increases to about 180,000 lbm (81,650 kg) for nonmanned cargo, and nearly 9,200 lbm (4,170 kg) larger than this figure for each 1,000 lbm (454 kg) of shielding required by

the nuclear stage in case personnel constitute part of the cargo carried. For Earth-escape maneuvers (unmanned), the corresponding numbers are 125,000 lbm (56,700 kg) and 244,000 lbm (110,680 kg).

2. The performance of two-stage chemical systems is superior to that of single-stage nuclear systems for Earth-escape missions with nonmanned payloads less than about 16,000 lbm (7,260 kg). Performance of a combination of a nuclear and a chemical stage, as opposed to that of two chemical stages, is better for initial masses larger than about 135,000 lbm (61,240 kg).

3. Uncertainties as large as 10 percent in nuclear stage inert weights could significantly alter the boundary curves and lead to different competitive stage weights.

4. The use of a 75,000-lbf nuclear rocket stage in all single-stage near-Earth orbital applications raises the equal-performance boundaries by about 15 percent compared with the use of stages having thrust levels tailored to give near-optimum thrust-to-initial-mass ratios. For Earth-escape missions, the use of the 75,000-lbf nuclear engine rather than of engines sized for near-optimum initial accelerations imposes little or no penalty in performance and the boundaries are essentially unchanged.

5. If propulsion stages were to be designed for a particular mission payload and ΔV requirement, the effects of applying them to missions of lower ΔV would be to increase slightly the equal performance boundaries obtained for single-stage nuclear and chemical stages designed specifically for each mission. For missions with ΔV requirements larger than the design ΔV, the equal-performance boundaries of the fixed stages are lower than for variable-size stages, particularly in the case of the initial-mass boundary.

National Aeronautics and Space Administration
Moffett Field, Calif., 94035, April 7, 1971

APPENDIX A

PROPULSION SYSTEM PARAMETERS AND SCALING LAWS

This appendix presents the nominal propulsion system characteristics chosen for this study. Mass units are in kilograms unless otherwise noted.

Specific Impulse

Chemical: 456 s
Nuclear: 825 s

Engine Mass

Chemical: $M_E = 0.0125\ T_c + 45$ (ref. 4)

where the thrust level of the engine T_c is taken as 0.4 of the initial mass for near-Earth orbital maneuvers and 0.5 for Earth-escape missions.

$$\text{Nuclear: } M_E = 21{,}093 + 1.582\times10^{-2}\ T_N + 4.835\times10^{-7}\ T_N^2$$

for M_E (lbm) and T_N, the nuclear engine thrust (lbf) or

$$M_E = 9568 + 1.582\times10^{-2}\ T_N + 1.066\times10^{-6}\ T_N^2$$

for M_E in kg and T_N in kgf, or

$$M_E = 9568 + 1.6132\times10^{-3}\ T_N + 1.1084\times10^{-8}\ T_N^2$$

for M_E in kg and T_N (newtons). These equations were derived by fitting a curve that paralleled earlier data for nuclear engine mass as a function of thrust in the case of engines designed for maximum full-thrust lifetimes of about 60 minutes, but included a current estimate of 25,000 lbm for a 75,000-lbf engine capable of long life (perhaps 10 hr) and of numerous restarts. This mass includes allowance for shielding of engine components and of propellants but not for crew-carrying spacecraft. For application of the nuclear engine for orbital maneuvers near Earth, the thrust level is selected to give an initial acceleration of 0.2 g. Gravity losses for such maneuvers are negligibly small at this value of thrust-to-weight ratio so long as escape velocity starting from a low parking orbit is not exceeded. For maneuvers resulting in hyperbolic excess speeds greater than zero, it is found that for initial masses less than about 68,000 kg (150,000 lbm) an initial thrust-to-weight ratio of 0.4 provides essentially maximum performance over a wide range of V_∞ (hyperbolic excess speeds). Here gravity losses are not negligible, particularly at large V_∞, and are taken into account.

Propellant-Module Mass

An empirically derived scaling law for the structural mass M_S of propellant modules (ref. 4) is used here for both the chemical and nuclear stages, namely,

$$M_S = (A/\rho^{0.533})M_P^{0.9} + 500$$

where A is a constant with a nominal value of 0.10, ρ is the specific gravity of the propellant(s), and M_P is the mass of usable propellant(s). For the bipropellant chemical systems it is assumed that the liquid hydrogen and liquid oxygen are stored in a single tank with a common bulkhead. An oxidizer-to-fuel ratio of 5:1 is adopted for the present purpose.

REFERENCES

1. Sandri, R.: Nuclear-Thermal Versus Chemical Drives for Super-orbital Velocities. *J. Spacecraft and Rockets,* vol. 1, no. 5, Sept.-Oct. 1964, pp. 568-569.

2. Clark, M. K.; Sagerman, G. D.; and Lahti, G. F.: Comparison of Small Water-Graphite Nuclear Rocket Stages With Chemical Upper Stages for Unmanned Missions. NASA TN D–4827, 1968.

3. Dugan, D. W.: The Role of Staged Space Propulsion Systems in Interplanetary Missions. NASA TN D–5593, 1969.

4. Gogolewski, R.; Ragsac, R. V.; Thrasher, G.; and Titus, R. R.: Study of Trajectories and Upper-Stage Propulsion Requirements for Exploration of the Solar System. Final Report, NASA Contract NAS2–2928, NASA CR–80297, 1966.

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