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AEC RESEARCH AND
DEVELOPMENT REPORT

GA-9046

REACTOR REQUIREMENTS FOR FIRST GENERATION
THERMIONIC NUCLEAR ELECTRIC PROPULSION

by

J. F. Ingber and D. T. Higdon

Prepared under
Contract AT(04-3)-167
Project Agreement No. 14
for the
San Francisco Operations Office
U. S. Atomic Energy Commission

November 1, 1968

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INTRODUCTION

The flight readiness of a nuclear electric propulsion system will be determined, to a large extent, by when the reactor lifetime can meet or exceed the operational thrust time requirements of the proposed missions. In turn, the demonstration of these lifetimes depends on when a power level is selected and construction of a prototype reactor begun.

The demonstration of the performance potential of nuclear electric systems has often involved a flight mode and assumptions which place stringent requirements on reactor development for near-term application. In particular, reactor lifetime has been treated as an unconstrained variable which results in enhanced performance estimates. Often, this involves payloads in excess of those projected as being necessary during the contemplated flight periods. An arbitrary mission model should not be permitted to determine the readiness or usefulness of an advanced system. Rather the determination should be made on the basis of the system's ability to perform useful missions using existing technology.

A study conducted during the last year at Gulf General Atomic (Ref. 1) has described optimum performance and useful launch vehicle-power plant combinations for a wide range of nuclear electric solar system missions. Perhaps the most significant aspect of this analysis is the ability to view the numerous tradeoffs possible with an electric propulsion system and to

quickly assess optimum performance with major variable constraints -- namely, chemical hyperbolic injection velocity, initial acceleration level, and the thrust time of the electric vehicle. Many launch vehicles, representing a wide range of payload capability, were investigated. A Titan III F/Centaur was selected as a representative launch configuration for planetary missions coupled with a 50 to 100 kWe nuclear electric propulsion system.

This document addresses itself to the question of establishing a power level and reactor lifetime requirements for first generation unmanned nuclear electric propulsion application, while considering in detail relevant mission-related technology constraints, and describing the performance capabilities of such a system.

ASSUMPTIONS

The analysis presented here is for a two-body planar problem with circular planetary orbits. The planets considered and their semi-major axes (assumed radial distances from the sun) are given in Table 1. The Earth escape mode is chemical to some hyperbolic velocity which is treated as a free variable.

Two basic types of missions were considered. The flyby intercepts the target planet in the specified time with no restriction on its terminal velocity. The capture mission assumes a zero-relative velocity with respect to the target planet at encounter and so is equivalent to a weak planetary orbit when n-body effects are taken into account. The optimization involved the maximization of the vehicle's final mass with a specified power level. Power conditioner efficiency was assumed to be 0.91. Thrustor efficiency curves are discussed in detail later.

Based on the previous analysis mentioned, two power levels were selected. The 100 kWe size is nearly optimum for the Titan/Centaur launch vehicle and so would come close to duplicating the maximum performance expected, while the 50 kWe reactor is near the minimum usable size for prime propulsion on this vehicle. Also, a 50 to 100 kWe thermionic reactor is considered desirable in order to satisfy auxiliary power requirements on many missions. Nuclear thermionic power plant mass

information on these two power levels, generated at Gulf General Atomic, have been used in the study, and the relevant information is given in Table 2. It should be emphasized that for purposes of this analysis, the reactor masses quoted can be treated as reference values. Therefore, the payload information may be adjusted on a one-to-one basis in response to future refinements of the mass estimates. The same applies to using the U^{235} fuel instead of the nominally assumed U^{233} .

At this time, estimates of payload requirements are somewhat arbitrary and controversial. It may be reasonable, however, to suggest lower limits on payload requirements based on an extrapolation of our past planetary program requirements. The Mariner Mars and Venus spacecraft weighed between 200 and 400 kg. Lunar Orbiter was about 400 kg, and the Surveyor spacecraft on the Moon has a mass under 300 kg of which there is a 50 kg package of science. Since this study deals with general solar system exploration, such a limit should reflect minimum capability to the farthest planets. It was assumed that 1000 kg is an acceptable minimum for any mission considered here, half of which could probably be science. This resulted in a range of flight times extending out to about six years at Pluto without any planetary swing-by assists.

The term payload is defined as the vehicle's final mass at the target minus the entire propulsion system. Note that power requirements consistent with the science package, navigation, and communication systems which are a significant fraction of a chemically propelled spacecraft's payload are not here considered as payload.

RESULTS

OPTIMAL PERFORMANCE

The study was initiated with the computation of optimum performance to the planets for both power levels (50 and 100 kWe). Thrust times were not constrained. Figures 1 and 2 summarize these results. While the data is shown for the U^{233} fueled system, it is clear that at this point the U^{235} associated masses would also yield quite acceptable performance. Also significant is the fact that the 50 kWe system holds up well over all the missions. Comparison of the 100 kWe data with optimum power results (Ref. 1) is very close, as expected. This insensitivity of payload to power variations around the optimum is a significant characteristic of nuclear electric systems (to be discussed later).

THRUST TIMES

Approximate thrust times for these missions are summarized in Fig. 3. The actual times are fairly insensitive to the target planet and power level. The optimal thrust times of 20,000 to 30,000 hours to Neptune and Pluto should not be construed as being essential for these flights. The fact is that technology dictates mission constraints, and that a mathematical optimization exercise without imposing these constraints is misleading.

The development goal of a 10,000-hour thermionic cell lifetime has

generally been assumed analogous to a statement of minimum reactor lifetime. This number has been questioned as being unrealistic in light of the thrust times just discussed.

As Figs. 4 and 5 show, the imposition of a 10,000-hour thrust constraint produces a payload capability across the solar system still within our projected requirements and on some missions is nearly indistinguishable from the unlimited thrust case. The effect of major thrust time reductions on the 50 kWe system now becomes prominent. Nevertheless, the 10,000-hour constraint is generally a mild perturbation on performance capability--certainly for the major planets which presently hold the greatest interest for future exploration. In the case of Jupiter, there is practically no change in performance which stems, primarily, from the optimally short thrust times associated with this body. Similar features are noted for Saturn. The relative insensitivity of performance to thrust time is realized by the significant tradeoff capability of the system parameters, and indications were that these could be pushed still farther.

The Jupiter flyby in Fig. 6 withstands thrust time reductions under 2500 hours retaining considerable performance. The Jupiter capture in Fig. 7 for a 100 kWe system still shows comparatively good performance between 2500 and 5000 hours. The 50 kWe system on this same mission, Fig. 8, causes performance to fall off quickly and now necessitates longer flight times to attain acceptable payloads with reduced thrust times. The substitution of U^{235} fuel here would not yield the required performance.

Finally, a Saturn flyby in Fig. 9 shows the acceptability of bringing mission thrust requirements into line with projected technology capabilities.

LAUNCH WINDOWS

Equally important in a mission study is the launch window available. Typically, low thrust vehicles have large comparatively flat windows. However, the data presented here were generated for an optimum central angle of travel, and so it is necessary to view performance across the window and with reduced thrust times. As shown in Fig. 10, a Jupiter capture generates a window covering a span of two-thirds of any year. A thrust time reduction to 5000 hours still provides a four-month window with a 1000 kg payload. For missions to planets farther out in the solar system, the launch window constraints are even more relaxed. For instance, a Uranus flyby in Fig. 11 produces a nearly flat window illustrating the fact that the concept of a launch window loses significance for flights to distant planets with electric propulsion. In effect, one can launch any time.

REACTOR POWER LEVELS

The final mass of a vehicle as a function of reactor power on a 600-day Jupiter capture mission is given in Fig. 12. On the same plot are shown propulsion system mass curves for the U^{233} and U^{235} fueled reactors obtained from the data in Table 2. The difference between these two functions is the payload. When the slope of the propulsion system mass line

equals that of the final mass curve, the optimum power is defined. Most significant is the fact that over a wide range of powers about the optimum these slopes are practically the same, the higher powers producing the smaller payload differences. As the power level is increased beyond the optimum, the increased propulsion system mass is nearly offset by the reduced propellant mass resulting from higher exhaust velocities. Therefore, there is no significant performance disadvantage in going to higher than optimum power, while lower than optimum powers can be used with little loss in payload. An increase in the slope of the propulsion system mass line will indicate lower powers for the same mission, while a decrease in this slope, reflecting an economy in the large sizes, suggests a higher optimum point.

As Fig. 13 shows, the change in flight time to 800 days is insignificant in determining an "optimum" power level. This stems from the fact that making the mission easier with an already adequate power level just shifts the mass curve up without changing its shape. This is the prime mechanism for increasing payloads. Also of great importance, as illustrated in Figs. 12 and 13, is the fact that thrust time reductions to 5000 hours do not significantly change the shape of the final mass curve. This implies that there is not much to be gained by increasing power levels on reduced thrust time missions.

A 1600-day Uranus flyby in Fig. 14 generates the same picture, indicating that the optimum power level is not very sensitive to the mission.

LAUNCH VEHICLE

If the launch vehicle were changed from a Titan III F/Centaur to a Titan III D/Centaur, Fig. 15, we note a significant change in the optimum point, Fig. 16. As expected, the smaller vehicle calls for a smaller power plant, and the latitude in the selection of the point decreases. Smaller vehicles have less tradeoff capability than do large ones and consequently are more sensitive to system variations.

A similar final mass curve could be constructed for any launch vehicle having similar payload-velocity excess relationship by estimating the injection velocity at a given power level and scaling the final mass curves and the power level by the ratio of the launch vehicle masses at that point. This, in effect, produces the same acceleration profile for both vehicles and, therefore, duplicates the mission. So, while the mission or mission time does not appreciably affect the power level selection, the launch vehicle does.

THRUSTOR EFFICIENCY

Thrustor performance is of major importance in electric propulsion mission analysis. Figure 17 shows the electrical and mass efficiencies that were assumed in the analysis. Common to all plasma thrustors, at the present, is a rapid drop-off of efficiency at low exhaust velocities. It is informative to project on payload improvement potentially available from these devices or to assess performance degradation using the present technology that has been assumed. This is analogous to viewing performance

with unlimited thrust times as we did initially. Figure 18 illustrates this payload gain on an 800-day Jupiter capture mission when the thruster electrical and mass efficiencies are assumed to be 0.9 and 0.95, respectively, over the entire exhaust velocity range. The most dramatic changes occur at the short thrust times where it is necessary to lower the exhaust velocity in order to increase the vehicle acceleration level. At longer thrust times and out to the optimum time, the payload differences are less significant. This is due to the optimization selecting operating points away from the inefficient exhaust velocity region. Only a requirement for increased acceleration, like with a limited thrust time or a very short mission time, will cause the exhaust velocity to be driven into this inefficient region. As shown in Fig. 19, the improved efficiency curves for a fixed thrust time generate a higher operating exhaust velocity than do the nominal efficiencies. In effect, the higher efficiencies produce the equivalent of a larger power plant for a fixed thrust time which, as discussed before, then converts this "excess" power into a higher exhaust velocity. There is considerable activity being directed toward the efficiency improvement of ion thrusters at low exhaust velocities. Such technology advances will further enhance the role that first generation reactor systems can play.

CONCLUSIONS

The establishment of payload requirements is, perhaps, the prime factor in selecting a launch vehicle; and the launch vehicle, in turn, essentially dictates the power level. For a given vehicle, power is fairly insensitive to changes in mission and mission times. Furthermore, reactor lifetimes do not significantly influence power selection.

For the Titan III F/Centaur vehicle considered, both the 50 and 100 kWe systems produce adequate results for unlimited thrust times. When these times are greatly reduced, the 100 kWe system shows definite advantages. In fact, the 100 kWe system yields about as good performance as any power plant in the 50 to 150 kWe range.

The differences between a U^{233} and U^{235} fueled reactor are not crucial for optimum thrust times. Reduction of thrust times to near 5000 hours almost necessitates the use of U^{233} fuel in order to attain adequate performance.

Thrust times of 20,000 to 30,000 hours are not necessary in order to perform useful missions. Any planet in the solar system can be reached with adequate performance using 10,000 hours of thrust. As has been demonstrated here, missions to Jupiter and Saturn may be performed successfully with 5000 hours of thrust. Reactor lifetime requirements for

first generation thermionic nuclear electric propulsion should be consistent with these results.

This document has dealt with nuclear thermionics for prime propulsion. Application of the power source for experimental purposes would necessitate a redefinition of the vehicle's payload. One would then have to superimpose this additional reactor operating time on the propulsion requirements. The operational mode of the reactor during coast periods could also contribute to increased lifetime requirements.

TABLE 1
PLANETARY DISTANCES

Planet	Semi-major Axis (AU)
Jupiter	5.20
Saturn	9.54
Uranus	19.18
Neptune	30.06
Pluto	39.52

TABLE 2
PROPULSION SYSTEM MASSES

Component (kg)	Type			
	U ²³³		U ²³⁵	
	50 kWe	100 kWe	50 kWe	100 kWe
Reactor	297	510	420	667
Shield	208	311	262	348
Heat Rejection	207	470	656	842
Thrustors and Power Conditioner*	400	550	400	550
TOTAL (kg)	1112	1841	1738	2407

*Power conditioner mass assumed 3.64 kg per kW out of PC. Twenty-five percent redundancy assumed on thrustors and power conditioner. Thrustors' diameter optimized with a minimum of four thrustors. Mass factor of two included to account for frame, spares, transmission lines, and shield.

Fig. 1. Titan III F/Centaur/Nuclear Electric Propulsion.
100 kWe (U^{233}) system - optimum performance

Fig. 2. Titan III F/Centaur/Nuclear Electric Propulsion.
50 kWe (U^{233}) system - optimum performance

Fig. 3. Titan III F/Centaur/Nuclear Electric Propulsion.
Approximate optimum thrust times
for all missions considered

Fig. 4. Titan III F/Centaur/Nuclear Electric Propulsion.
100 kWe (U^{233}) system - 10,000 hr thrust

Fig. 5. Titan III F/Centaur/Nuclear Electric Propulsion.
50 kWe (U^{233}) system - 10,000 hr thrust

Fig. 6. Jupiter flyby. Titan III F/Centaur/Nuclear Electric Propulsion. 100 kWe (U^{233}) system - limited thrust times

Fig. 7. Jupiter capture. Titan III F/Centaur/Nuclear Electric Propulsion. 100 kWe (U^{233}) system - limited thrust times

Fig. 8. Jupiter capture. Titan III F/Centaur/Nuclear Electric Propulsion. 50 kWe (U^{233}) system - limited thrust times

Fig. 9. Saturn flyby. Titan III F/Centaur/Nuclear Electric Propulsion. 100 kWe (U^{233}) system - limited thrust times

Fig. 10. 800-day Jupiter capture. Titan III F/Centaur/Nuclear Electric Propulsion. Launch window

Fig. 11. 1600-day Uranus flyby. Titan III F/Centaur/Nuclear Electric Propulsion. Launch window

Fig. 12. 600-day Jupiter capture. Titan III F/Centaur/Nuclear Electric Propulsion. Power vs. final vehicle mass for optimum power selection

Fig. 13. 800-day Jupiter capture. Titan III F/Centaur/Nuclear Electric Propulsion. Power vs. final vehicle mass for optimum power selection

Fig. 14. 1600-day Uranus flyby. Titan III F/Centaur/Nuclear Electric Propulsion. Power vs. final vehicle mass for optimum power selection

Fig. 15. Launch vehicles

Fig. 16. 1600-day Uranus flyby. Power vs. final vehicle mass for optimum power selection for a Titan III F and Titan III D booster

Fig. 17. Thrustor efficiencies vs. exhaust velocity

Fig. 18. 800-day Jupiter capture. Titan III F/Centaur/Nuclear Electric Propulsion. Payload increase for potential thruster improvement

Fig. 19. 800-day Jupiter capture. Titan III F/Centaur/Nuclear Electric Propulsion. Exhaust velocity vs. thrust time

REFERENCE

1. Ingber, J. F., "Thermionic Nuclear Electric Propulsion, Sizing and Performance," Gulf General Atomic Incorporated Report GA-8684, June 1968.