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NUCLEAR PULSE VEHICLE STUDY CONDENSED SUMMARY REPORT (GENERAL DYNAMICS CORP.)

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, AL

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NUCLEAR PULSE VEHICLE STUDY

CONDENSED SUMMARY REPORT

NASA Contract NAS 8-11053

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NUCLEAR PULSE VEHICLE STUDY

CONDENSED SUMMARY REPORT

TO
GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA

Contract NAS 8-11053

14 Jan, 1964.

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Agencies and

FOREWORD

Technical studies on nuclear pulse propulsion were initiated in 1957 by the General Atomic Division of General Dynamics Corporation. Early governmental support was awarded in 1958, initially from the Advanced Research Projects Agency (ARPA). From 1960 to the present, the research support has been continued by the United States Air Force and by General Dynamics Corporation. In July, 1963, the Marshall Space Flight Center of the National Aeronautics and Space Administration initiated an applications study with General Atomic for determining possible NASA-oriented mission applications of nuclear pulse propulsion, for obtaining a better understanding of key operational questions and potential hazards, and for studying implications to other proposed future NASA programs.

Summarized here are the results of the mission-oriented applications study performed for NASA under Contract NAS 8-11053. The study is treated more fully in the expanded summary report and in the technical report on the *Nuclear Pulse Vehicle Study,* both of which are to be issued subsequently.

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CONTENTS

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1. INTRODUCTION

Over six years of continuous and intensive analytical and experimental research have been concentrated on nuclear pulse propulsion. This propulsion concept — a prime example of the peaceful application of nuclear explosions — offers performance potential for realizing economic manned space travel to any part of our solar system.

A nuclear pulse propelled vehicle is shown conceptually in the frontispiece. Briefly, the propulsion system operates as follows: Low-yield nuclear pulse units are detonated sequentially external to and below the vehicle. A substantial fraction of the mass of each pulse unit — the propellant — is directed toward the bottom of the vehicle as a high-velocity, high-density plasma which is intercepted by a large circular metallic plate — the pusher. The momentum of the propellant is transferred to the pusher and the resulting accelerations are smoothed out by shock-absorbing devices to levels of a few *g*'s in the upper vehicle — well within human tolerance. System performance is characterized by both high thrust-to-weight ratios and large specific impulses.

The research effort, about half of which has been experimental, was directed initially to demonstrating scientific feasibility. Now that the concept appears to be feasible without new "inventions," the current effort includes determining the engineering practicality of the concept through integrated propulsion-system design studies and applied research programs to provide technical information relating to pulse-unit design, pusher ablation, and structural integrity of the pusher attachments and shock-absorbing systems.*

Earlier design studies concentrated on vehicles of large sizes (4,000 tons) and high specific impulse (4,000 to 6,000 sec) that would be capable of direct launch from the earth's surface or suborbital start-up and would have a vehicle thrust to weight ≥ 1.25 *g*. Such vehicles would have propulsion-module inert-weight fractions of 0.3 to 0.4 and pulsing intervals of about 1 sec. During the current applications study, it became evident that NASA mission constraints on the propulsion system were far less demanding, which tended to relieve design and operational problems, improve reliability, and increase over-all system performance. For example, NASA mission requirements allow orbital nuclear start-up, with rendezvous, which in turn will permit:

- Selection of near-optimum vehicle thrust-to-weight ratios.
- Lower inert-weight fractions, higher payload fractions, higher mission velocities.
- Greater time spacing between nuclear pulses.
- Lower net vehicle accelerations, simpler and more reliable designs, improved specific impulse for a given size.
- Possible elimination of fission products dispersed in the atmosphere.
- Elimination of long-term artificial electron belts.

These new considerations, together with recent advances in pulse-unit design, greatly enhance the mission capabilities of small propulsion modules that are compatible with the Saturn V:

Propulsion module weight	$\leq$200,000 lb
Inert weight fraction	10% to 20%
Specific impulse	1,800 to 2,500 sec
Propulsion module diameter	10 m

These smaller modules tend to be less efficient and may carry a larger nuclear-fuel inventory for a given mission, which increases the operating cost per unit payload over that of the larger, high I_{sp} vehicles. However, in comparison with other advanced propulsion systems for the 1970 era, the economics of the small vehicles are still very attractive. All of these factors, together with its desirable operational characteristics, make the Saturn V compatible module an interesting early development goal.

Further, this small propulsion module represents an early system capability that establishes a technology base from which gross performance improvements are indicated, leading to a true solar-system transportation capability. No major operational or fuel availability obstacles appear to preclude appropriate employment of nuclear pulse vehicles in the National Space Program.

Primarily because of the longer pulsing intervals allowable, a ground-oriented, phased, development plan appears practical, permitting not only prototype development but also prelaunch *qualification* of flight-rated operational propulsion modules at ground facilities.

A note of caution and of optimism must be injected here. Design data for the Saturn V compatible propulsion modules were not derived from specific point-design studies; they were obtained by scaling from much larger modules. Some performance inaccuracy may therefore exist. Design studies initiated too recently to be included in the present mission studies indicate that the scaled performance estimates used are probably conservative.

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*This work has been reported in *Technical Summary Report, Nuclear Pulse Propulsion Project (Project ORION)*, Air Force Systems Command, RTD TDR 63-3006, Vols. I-IV, 1963 (S-RD report) and in more than 300 technical reports that have been issued on the Project.

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2. STUDY OBJECTIVES

This seven-month study was performed to explore the mission potential of the nuclear-pulse space vehicle concept. A variety of space missions were considered for both "favorable" and "unfavorable" departure years and for near-term and long range. The study, of broad scope and limited depth, encompassed three primary and three secondary objectives:

Primary Objectives

1. Determining the mission potential of nuclear-pulse space vehicles for lunar and planetary missions in the time period between 1975 and 1995 for a variety of mission profiles and operational objectives.
2. Defining expected operational systems, operational problems, and possible approaches for solution to the problems.
3. Establishing typical development programs directed toward reaching major planetary mission capability in the 1975-1995 time period.

Secondary Objectives

1. Developing parametric propulsion-vehicle system design data in a form useful for the various mission studies.
2. Defining possible areas of growth or improvement in technology which would have a substantial influence on future performance, operations, or development programs.
3. Providing nuclear-pulse vehicle performance techniques capable of simulating flight and indicating performance for any given vehicle.

3. RELATIONSHIP TO OTHER NASA EFFORTS

The nuclear pulse space vehicle, assuming that its operational potential approaches that indicated by this study, would appear capable of having a strong influence on future NASA programs during and beyond the 1970's. At least three areas of NASA effort could be affected: (1) studies and eventual execution of lunar and planetary exploration and transportation, (2) the earth-launch-vehicle programs, and (3) operational sites and ranges.

LUNAR AND PLANETARY EXPLORATION AND TRANSPORTATION STUDIES

There are several significant operational and economic advantages for nuclear pulse propulsion in its initial realm of operation — earth orbit to the lunar or planetary orbit and return. A major operational advantage is that it is capable of performing *with a single stage* the complete round trip. The crew need master only *one* restartable propulsion system, which they can exercise prior to departing earth orbit on a difficult mission and, if necessary, maintain or service during the mission.

An economic advantage appears evident primarily for two reasons: (1) one stage, instead of several, for interorbit flight operations reduces the required over-all development task, interface and staging complexities, and series reliability requirements, all of which are very costly, and (2) relatively low earth-orbit departure weights keep down the boost-to-orbit costs, which typically predominate the economics of such missions.

EARTH-LAUNCH-VEHICLE (ELV) PROGRAMS

The mode of operation most compatible with NASA's near-future requirements is an orbital start-up of the nuclear pulse vehicle, with conventional ELV's employed for the important boost to orbit. Saturn V appears to be appropriate for a considerable period of time for space exploration and transportation.

For the post-Saturn era, tentative ELV requirements for the nuclear pulse vehicle are low-aspect-ratio ELV configurations to match the relatively large diameters of larger nuclear pulse vehicles and ever-improving booster economics, both of which tend to favor recoverable boosters.

OPERATIONAL SITES AND RANGES

The operations, sites, and facilities for nuclear pulse propulsion will introduce some new operational considerations, primarily in the handling, loading, and launching of nuclear fuel and high explosives. Here the utilization of AEC and military experience seems logical.

To eliminate fission-product fallout or the trappage of electrons in artificial radiation belts, some different constraints on earth-orbit departure trajectories may be required. These, in turn, may be reflected in modified boost-to-orbit trajectories, range-safety considerations, etc.

A preliminary investigation of basing requirements indicates that modest modifications to the now-programmed Cape Kennedy facilities will be required to support Saturn V-boosted nuclear pulse systems. No hazards are envisaged (for the orbital start-up mode) which would necessitate a launch site other than part of the Cape Kennedy complex.

4. METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

The study was divided into two phases: a parametric phase to explore a very broad range of sizes and mission capabilities and then a specific-conceptual-system phase to

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investigate in greater detail the mission capability of two selected sizes of nuclear pulse vehicles.

PARAMETRIC STUDY PHASE

Four tasks were performed during this phase of the study.

1. Parametric characteristics defining the performance and operation of nuclear pulse propulsion modules, as functions of effective thrust, were derived from earlier propulsion-system design studies over a wide range of thrust. These parametric characteristics are the *principal assumptions* of the study.

2. Vehicle systems were defined and "exercised" by computing their performance for a range of mission velocities encompassing the simpler and more difficult Mars explorations, lunar missions, and selected Jovian explorations. Concurrently, mission payload requirements were compiled. Three modes of operation (Fig. 1) were considered: (a) A self-boost-to-orbit mode, called operational Mode I, which requires an effective thrust-to-weight ratio >1.0 to escape the earth's gravity. (b) An orbital start-up mode, Mode III, in which the nuclear pulse vehicle is initially lofted to orbit by a chemical booster. The thrust-to-weight ratios for Mode III can be well under 1.0. (c) An intermediate Mode II in which the propulsion module is loaded in orbit after self-boosting.

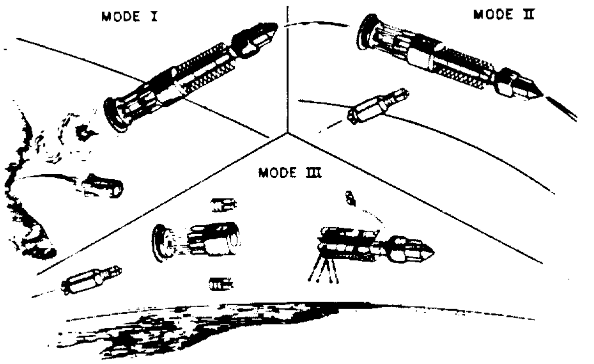

Fig. 1 — Operational modes

3. Comparative direct operating costs and the major cost components were computed in a simplified cost analysis to derive the more economical operating modes and vehicle sizes over the broad range of nuclear pulse systems being explored.

4. Operational problems and hazards unique to nuclear pulse propulsion were explored so as to define and quantify, to first order, the magnitude of the problem and to identify those problem areas that require further attention.

SPECIFIC-CONCEPTUAL-SYSTEMS STUDY PHASE

During the second study phase, five tasks were performed; the major portion of the contractual effort, however, was devoted to the first three.

1. Two specific nuclear pulse propulsion modules were defined in conjunction with specified manned payloads for a variety of Mars and Jovian explorations, for Mars logistic delivery, and for lunar logistic and personnel transport. The propulsion modules were sized to be compatible with earth launch vehicles planned for the same time periods. The Saturn V compatible module, a 10-m-diameter (32.8-ft) configuration, received particular emphasis after it appeared capable of more than adequately performing most of the exploration and space logistic tasks of early interest. The second module, of 20-m-diameter (65.6-ft), is compatible with post-Saturn design concepts.

2. Performance and approximate direct costs were determined for the space missions mentioned above.

3. A sensitivity analysis was made by varying, one at a time, the more suspect vehicle-performance or unit-cost inputs and recomputing the total mission performance or costs.

4. A tentative development plan and schedule was generated for an orbital start-up 10-m propulsion module.

5. Advanced versions of nuclear pulse vehicles and their performance and economic potential were reviewed. These data are based on performance characteristics predicted by exploiting known fundamental properties of nuclear fission and fusion devices.

5. BASIC DATA GENERATED AND SIGNIFICANT RESULTS

Most of the significant results of this study concern a 10-m-diameter propulsion module, which is about half the size of the smallest module that has previously received serious design consideration, but which has a very impressive (scaled) performance capability in the orbital start-up operational mode. Much of the credit for appreciating such a vehicle's capability goes to NASA for recognizing the logic and value in this size vehicle in spite of its poor propellant economics and comparatively degraded specific impulse.

SYSTEMS INFLUENCE FROM THE PARAMETRIC STUDY PHASE

The performance and operating economics of nuclear pulse vehicles are strongly influenced by two rather unique characteristics. One is the variation of specific impulse with

[redacted]

vehicle size, or with thrust if other operating conditions remain fixed. The nominal curve of specific impulse versus effective thrust used throughout most of this study is shown in Fig. 2. The curve indicates obvious performance advantage with increasing size or thrust.

The second characteristic is the variation of over-all propellant costs with size or thrust, as shown in Fig. 3. Propellant-unit cost decreases rapidly with increased size or thrust. Thus, larger vehicles are strongly favored from the viewpoint of direct operating cost per pound of payload delivered.

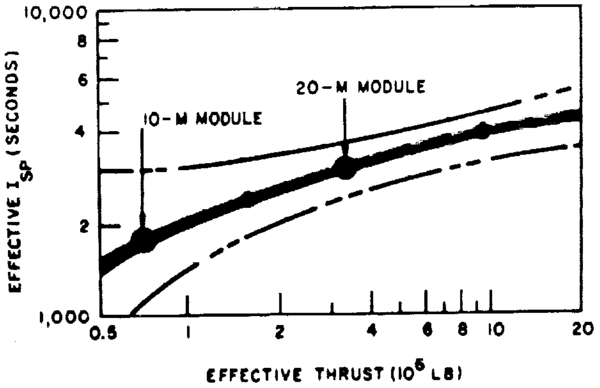

Fig. 2 — Propulsion-module specific impulse

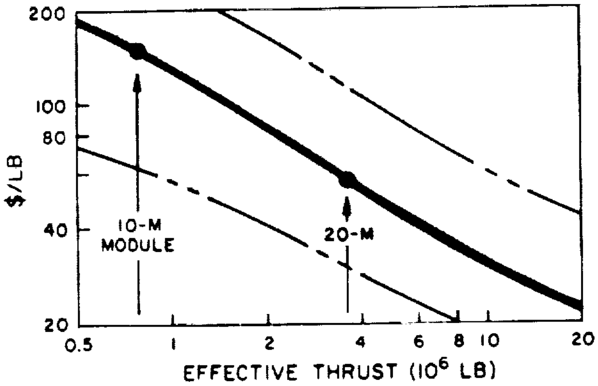

Fig. 3 — Over-all propellant costs

The most useful guidance from the parametric study phase comes from the performance benefits of an orbital start-up, reduced thrust-to-weight ratio, mode of operation. These benefits are seen in Fig. 4, where the single-stage payload delivery capability of typical nuclear pulse vehicles is shown for initial thrust-to-weight ratios of 1.25 and 0.25. At a thrust-to-weight ratio of 0.25, mission velocities of 100,000 fps are attainable with significant payloads at a thrust well under one million pounds.

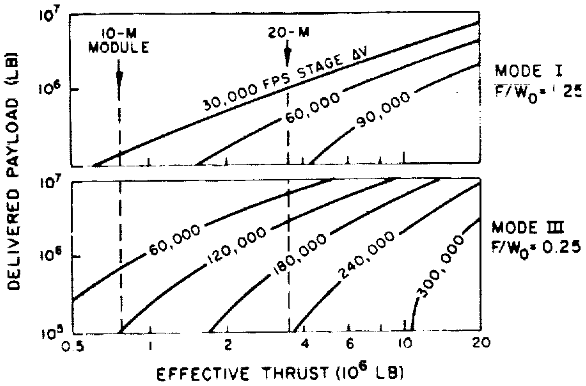

Fig. 4 — Typical payload capabilities

The definition of exploration mission payloads and mission requirements, the compatibility with Saturn V or other ELV's and their major facilities, and the evaluation of mission hazards associated with the various start-up modes of operation for early nuclear pulse systems were also derived from the parametric study phase.

THE 10-METER CONCEPTUAL VEHICLE SYSTEMS

The conceptual design of a 10-m propulsion module, as defined and "frozen" for this study, is shown in Fig. 5. The basic module can carry 900 pulse units internally in its "ready-to-fire" racks. Additional propellant may be carried external to the basic module in the expendable propellant magazines shown.

The payload and supplemental propellant region of manned vehicle configurations are atop and around a central payload spine, as shown. Support columns for the propellant magazines and for externally carried payload are located around the central spine.

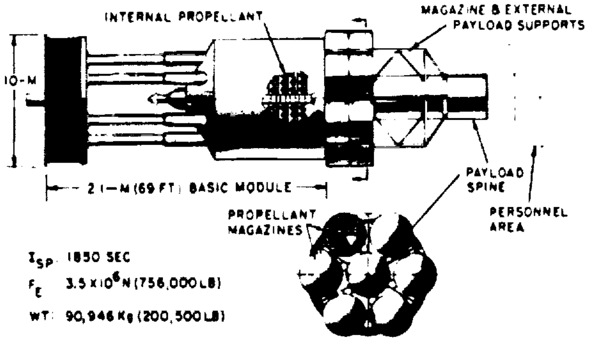

Fig. 5 — Ten-meter propulsion module

Compatibility with Saturn V

The 10-m-module configurations, as discussed previously, are compatible with the Saturn V earth launch vehicle. Typ-

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ical earth launch configurations are shown in Fig. 6. For the boost-to-orbit vehicles, the Saturn's orbital payload is 100,000 kg (220,000 lb) or less. The center boost-to-orbit configuration can carry not only the entire operational payload structure, all hardware, and most of a Mars mission expendables, but also two manned (or mannable) orbital assembly modules.

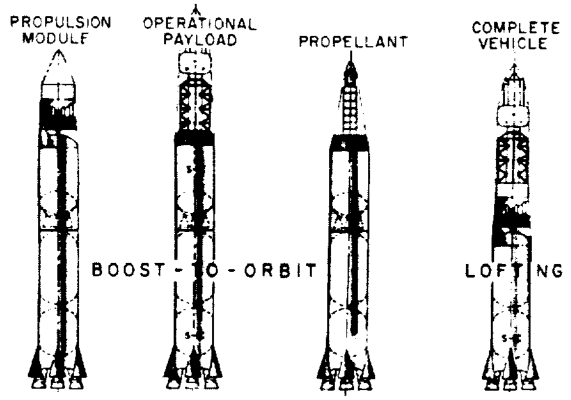

Fig. 6 — Module compatibility with Saturn V

For a suborbital start-up mode of operation, a complete, but ordinarily not fully loaded, 10-m nuclear pulse vehicle can be lofted to about 10,000 fps by a Saturn S-1C stage.

Personnel Shielding

During engine operation, all personnel are required to be within a shielded "powered flight station." Shielding requirements for this study have been based on an allowable propulsion dose of 50 rem per mission. These requirements result in a shaped shield of 25 g/cm^2 or more of hydrogenous material on all surfaces of the powered flight compartment. The compartment can therefore also serve as a solar "storm cellar."

Mars Exploration System Performance

Mars exploration vehicles using the 10-m propulsion module were conceptually designed and exercised on missions requiring velocities from ~50,000 to 100,000 fps. Departure weights and performance were computed for missions with and without destination payloads capable of providing manned landings on Mars, and for mission personnel complements of 8, nominally, or up to 20 persons.

An artist's conception of a two-vehicle convoy in earth orbit, being readied to depart for a manned surface exploration of Mars, is shown in Fig. 7. Each vehicle carries eight persons plus 75,000 kg of destination payload for use while in Martian orbit. For personnel safety, each vehicle carries food and ecology expendables for a double personnel complement for 290 days, the trip duration remaining after the Mars approach maneuver. The total mission velocity requirement is 72,850 fps, based on a 1975 departure and a 450-day mission that terminates with a 50,000 fps earth approach velocity.

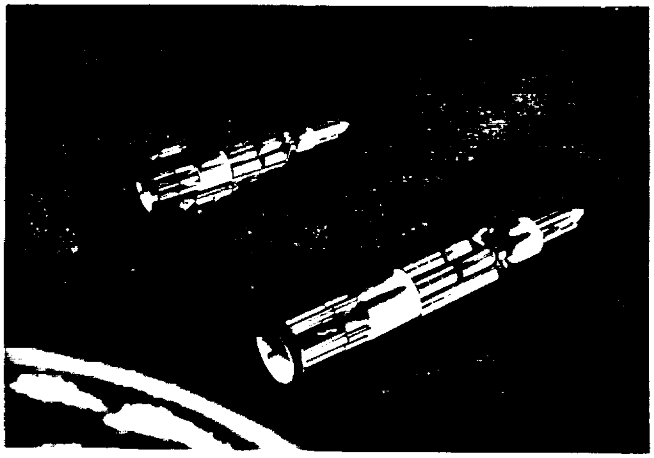

Fig. 7 — Two-vehicle convoy for Mars exploration

For the exploration mission depicted, each vehicle has an earth departure weight of 753,000 kg (1,660,000 lb). Eight successful rendezvous of Saturn V payloads are required to build up each vehicle of the two-vehicle convoy. For a single vehicle exploration (without the extra food and expendables) the departure weight is 741,000 kg (1,632,000 lb).

The effect of variations in the amount of destination payload and in number of exploration personnel is shown in Fig. 8. Each configuration employs the *same* basic 10-m propulsion module and operates through the same mission profile. The configuration shown in Fig. 7 is the center one in Fig. 8. The two 8-man configurations on the left carry as destination payload only 750 kg of mapping and data-storage equipment. Two 20-man configurations are shown on the right; one has a negligible destination payload, the other has 150,000 kg.

The effect of variations in mission velocity requirements is shown in Fig. 9. An 8-man, 450-day Mars operational payload and the small (750 kg) destination payload are carried in each vehicle. The configurations are identical except for variations in the reentry vehicle, when required, and in the quantity of propellant and propellant magazines. For the range of earth-orbit departure weights shown, four to nine successful Saturn V rendezvous are required.

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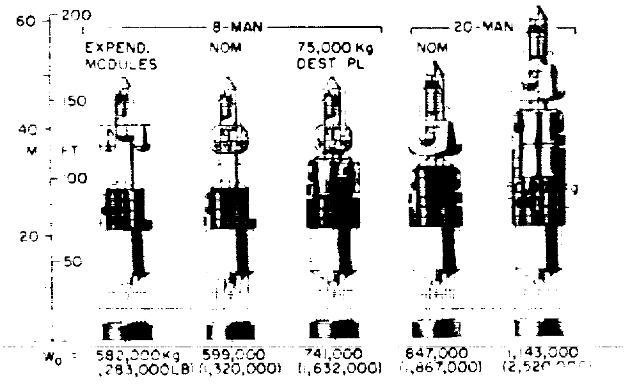

Fig. 8 — Variations in Mars-mission payload

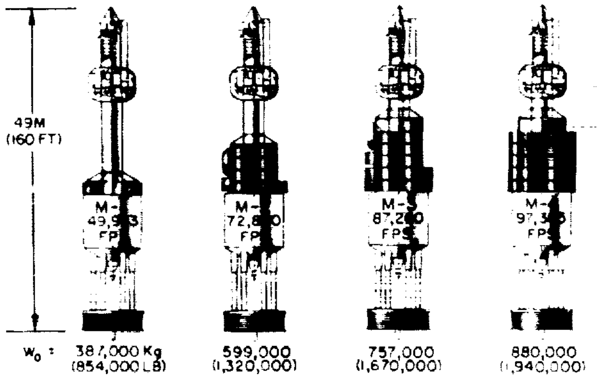

Fig. 9 — Variations in mission velocity

The range of mission velocities shown in Fig. 9 (based on the requirements of a 1975 departure) extends well beyond the range found in the cycle of "favorable" to "unfavorable" Mars departures. Departing on the most unfavorable year typically requires an 8% increase in departure weight, whereas the most favorable year permits a decrease of about 15%.

Direct-operating-cost comparisons and breakdowns for single-vehicle missions are shown in Fig. 10. The wider bars represent costs for the four mission velocities given in Fig. 9. The two narrower bars show cost differences for the M-2 case when carrying 75,000 kg of destination payload or when the personnel complement is 20 instead of 8. The latter comparisons indicate that useful payload could be more or less doubled at a direct mission cost increase of only one-third (presumably with little or no increase in the higher nonrecurring costs).

The earth-launch-vehicle (ELV) costs account for approximately 60% of total operations and the nuclear pulse propellant accounts for 20% to 30%. The comparatively small amount spent for the propulsion module indicates that it *should* be more expensive, if increasing its cost would improve the efficiency or weight so as to reduce propellant and/or boosting requirements.

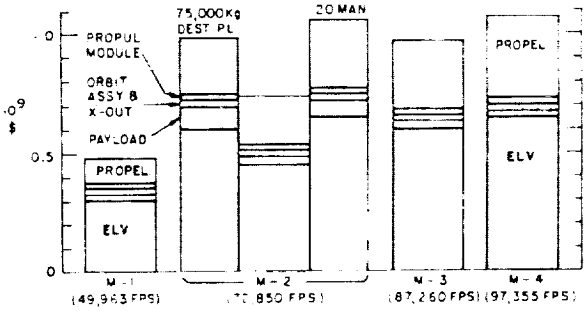

Fig. 10 — Mars-mission operating cost comparisons

The data of Fig. 10 *include* procurement of duplicate propulsion modules, payload sections, and redundant propellant and Saturn V operations to account for boosting, orbital mating, and loading probabilities. The probabilities used were 0.85 for successful orbital delivery, 0.97 for mating of propulsion module and payload section, 0.98 for loading propellant magazines, and 0.99 for loading destination payload. The over-all probability goal for orbital departure readiness was 0.75 or greater.

An abbreviated weight statement itemizing the make-up of the Mars exploration vehicle for both a Mars orbital and a Mars landing mission is given in Table 1.

Table 1

MARS ROUND-TRIP WEIGHT STATEMENT

(8-man, 450-day, M-2 Mission)

	Orbital Mission (kg)	Landing Mission (kg)
Operational payload	80,000	80,000
Intransit payload	250	1,000
Destination payload	750	75,000
Total payload weight	81,000	156,000
Propulsion module	92,430	93,800
Propellant magazines	13,735	16,785
Guidance and start-up fluids	6,570	7,235
Propellant	405,265	467,180
Earth-orbit departure weight	599,000 (1,320,000 lb)	741,000 (1,632,000 lb)

In reviewing the Mars exploration performance capability of the 10-m nuclear pulse configuration, no attempt has been made here to make comparisons with other space propulsion systems. It is believed that in numerous respects—e.g., single-stage round-trip capability, modest orbital departure weights, payload versatility, relative insensitivity to mission year or mission profile, etc. — the merits of the system for Mars, Venus, and other early explorations will be recognized.

Lunar Transport Systems Performance

Applications of the 10-m propulsion module to both a reusable lunar ferry and one-way expendable logistics vehicles were investigated. Large transport capabilities, in comparison with today's lunar base planning, are indicated. Here, again, the operating costs are dominated by the earth-launch-vehicle contribution.

The Lunar Ferry. An earth-orbit-to-lunar-orbit reusable ferry appears to be the better utilization of the nuclear pulse system for lunar base support. Figure 11 is an artist's conception of such a lunar ferry in operation, where passengers are transferring to lunar shuttles for descent to the lunar surface. The configuration shown carries 20 passengers per trip plus 200,000 kg (440,000 lb) of cargo for the lunar surface plus propellant for the lunar shuttle vehicles.

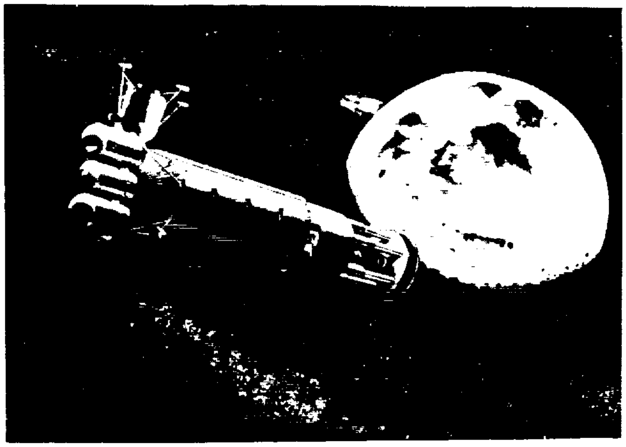

Fig. 11 — Nuclear pulse lunar ferry system

For most of the trip, the passengers occupy the passenger modules attached to the central powered-flight-station — command module. During powered flight, radiation-belt penetration, or solar storms, they would remain within the more compact, shielded, powered flight station.

The lunar-surface logistic capability of the above system is shown in Fig. 12. The delivered payload is seen to be relatively linear with departure weight, which indicates a wide range of payload capability per trip without greatly changing the delivery cost effectiveness (since delivery costs are largely a function of the mass required in orbit).

Preliminary estimates of direct operating costs for all elements of the system have been compiled and are summarized in Fig. 13. The cost estimate assumes a maximum stay time of 6 months for lunar-base personnel and a support requirement of 4,000 lb per man-year. The costs level off at about $7.5 million per man-year as the base size reaches several hundred men.

Figure 13 also shows a percentage breakdown of the operating costs, indicating that the two components that need minimizing are the earth-launch-vehicle operations and the nuclear pulse propellant. A reoptimization of the nuclear pulse propulsion parameters, for the lower velocities characteristics of lunar missions, may do much to reduce the latter. This reoptimization has yet to be performed.

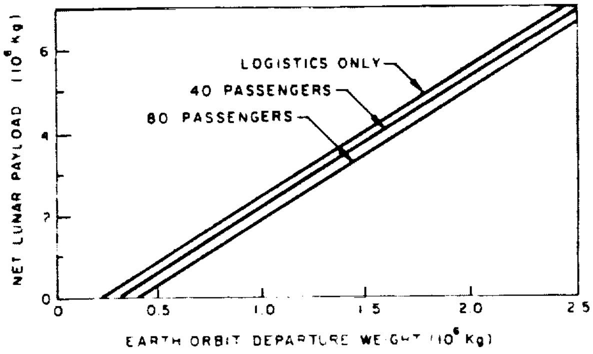

Fig. 12 — Lunar-base-support capability

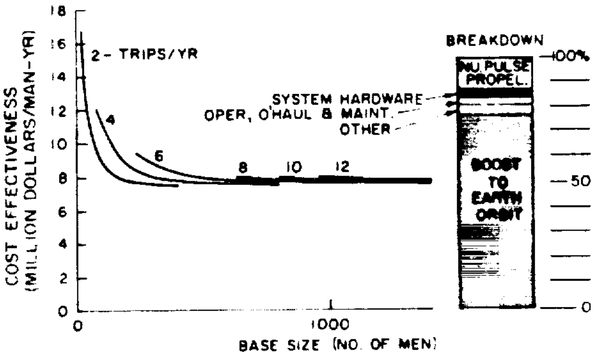

Fig. 13 — Lunar-base-support operating cost per man year

One-way Lunar Logistics Vehicles. Two methods of employing nuclear pulse vehicles expendably offer system gains in one-way logistic delivery to the lunar surface. One employs nuclear pulse propulsion from earth orbit to near the lunar surface and the other from near the earth (after lofting to about 10,000 fps by a Saturn S-1C stage) to near the

[redacted]

lunar surface. Both use chemical-rocket deceleration for the last 2,000 fps of lunar let-down.

A typical configuration for the earth orbit start-up mode of operation is shown in Fig. 14. With an earth-orbit departure weight of 1,800,000 kg (3,960,000 lb), this vehicle could deliver a payload of about 850,00 kg (1,870,000 lb) to the lunar surface. A similar but smaller vehicle, using an S-1C first stage, in a direct flight from the earth's surface could deliver approximately 67,500 kg (143,000 lb) to the lunar surface. A preliminary cost analysis indicates delivery costs of about $1500/kg for the earth orbit start-up mode and about $1600/kg for the direct-flight mode. These are about one-third the delivery costs when using an all-chemical Saturn V.

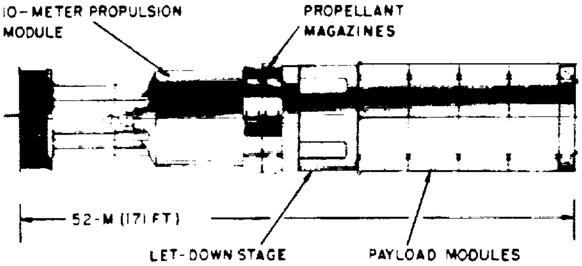

Fig. 14 — Orbital start-up lunar logistic vehicle

LARGER VEHICLE CAPABILITY AND GROWTH POTENTIAL

Two approaches can provide marked increases in system effectiveness beyond that shown for the 10-m configurations. The first, with the same state of the art as the 10-m designs, will capitalize on the increased specific impulse and reduced propellant cost per kilogram for larger vehicles. This approach is pictured in Fig. 15, where a 20-m diameter exploration vehicle is shown starting a maneuver to orbit Callisto, a moon of Jupiter. The 3,150-sec I_{sp} of this vehicle will permit, for example, a single-stage round trip to Jupiter, with a 20-man complement and 100,000 kg of destination payload. Such a mission will require a total mission velocity of 192,000 fps and a duration of 900 days. In Fig. 16, the conceptual design of a 20-m vehicle is shown in comparison with a 10-m Mars configuration.

The second approach to improve system effectiveness exploits more fully the potential of nuclear pulse propulsion. Pulse units having nuclear explosion devices designed specifically for propulsion purposes will be utilized, thus significantly improving propellant economics even for small vehicles. Advanced materials for propulsion module fabrication will also be utilized. For the post-1980 era, a specific impulse between 10,000 and 20,000 sec is predicted for vehicles somewhat larger than the 20-m vehicle depicted here.

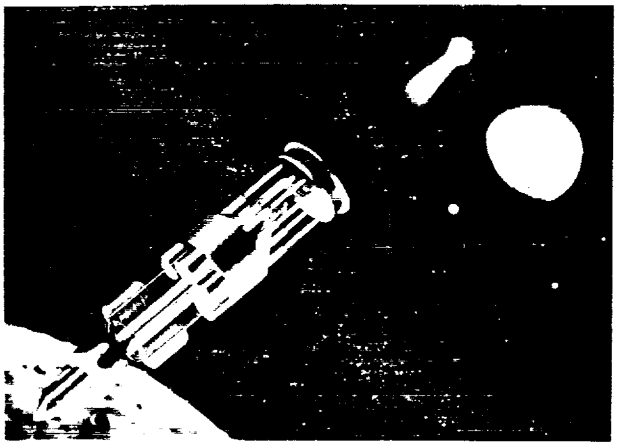

Fig. 15 — Jovian exploration vehicle

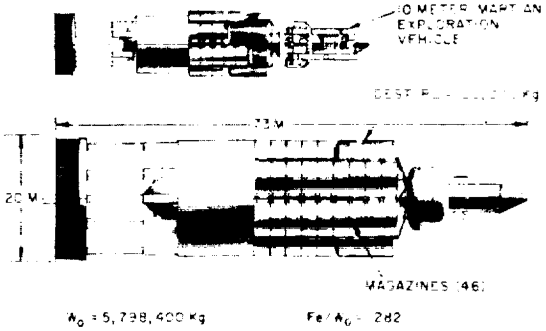

Fig. 16 — A 20-meter exploration configuration

OPERATIONAL PROBLEM CONSIDERATIONS

The more critical operational and hazards problems that are unique to nuclear pulse propulsion have been reviewed in relation to the launch complex, the earth's environment, the flight crew, and mission objectives to determine whether any fundamental characteristics might preclude or seriously constrain a major operational employment of nuclear pulse systems. These studies included various credible systems failures and resulting hazards, eyeburn to population, fission-product dispersal in the atmosphere, nuclear radiation levels during operations, creation of artificial electron belts, vehicle acoustical levels, and nuclear materials availability. Under the operational modes, constraints, and safeguards suggested, no issue under investigation to date appears to preclude

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large-scale employment of nuclear pulse systems for space exploration and transportation. Potential hazards to the earth's environments and population may not, in fact, be significantly different from those incurred by use of all-chemical systems.

DEVELOPMENT PLAN

Two new key research and development program elements are envisioned: (1) relatively inexpensive, contained, nuclear underground experiments to permit recovery of scaled to full-scale engine prototypes, and (2) repetitively placed high-explosive shock generators to attain time and spatial reproduction of the mechanical impulse received by the propulsion module at *full scale* and at the proper *firing rate*. These, plus other supporting techniques, permit a phased ground-based development program leading in well-defined stages to a Preliminary Flight Rating Test (PFRT) propulsion module for ballistic and finally orbital mission qualification. Preliminary studies indicate that the development program through orbital qualification should cost approximately $2 billion and require 12 years. Major program landmarks accrue at about 3-year intervals.

The fact that the same developmental techniques may later be used to prelaunch-qualify operational propulsion modules prior to commitment to manned space missions is of considerable operational importance.

6. STUDY LIMITATIONS

A major limitation of the study has been the lack of design data on small propulsion modules or on modules designed for orbital start-up. The findings of this study on the mission applications and capability of the smaller (10-m) modules has accentuated this limitation.

A secondary limitation, after determining the desirability of lower thrust-to-weight ratio start-up, has been the lack of time and data to "optimize" the orbital start-up operations. Several factors need to be considered simultaneously: gravity losses caused by reduced thrust-to-weight ratio, electron trappage (latitude) limitations, "multiburn" earth escape, launch-to-orbit ground-safety limitations, and coolant savings (I_{sp} gain) due to reduced thrust-to-weight ratios. In the current study, such optimization was of necessity neglected, again making the study results conservative.

A third limitation has been the limited depth of coverage of systems economics. There are many economic trade-offs that need exploration to understand and optimize the system parameters. This study has pointed out the importance of propellant economics and the relative unimportance of propulsion module hardware cost in the smaller thrust designs. (Thus, more should be spent on hardware if a reduction of mass or in propellant consumption, etc., can be realized.)

7. IMPLICATIONS FOR RESEARCH

Technical feasibility of nuclear pulse propulsion now seems reasonably assured; the major elements of a ground-oriented development plan have been identified and appear practical; current application studies confirm a revolutionary improvement in space operations if pulse propulsion can be developed and utilized. However, as in any new technology, a significant amount of basic knowledge and understanding should be generated, as well as a compelling reason for being, before any large-scale development effort is undertaken.

The immediate research objective, therefore, is to augment present technical knowledge in the more sensitive areas so that continued successful progress may lead rationally to a stepwise development program, provided, of course, that the payoff remains as relatively attractive as it does now. A well-balanced research program to attain this objective should contain, at least, the following major elements:

Design studies, including pulse-unit designs and ablation calculations, to evolve optimum propulsion module designs compatible with vehicle sizes and operational modes now of interest to the National Space Program.

Underground nuclear tests and continued HE ablation experiments to correlate ablation and other early-time interaction phenomena with calculations, under conditions of propellant velocities, temperatures, pressures, densities, and scales relevant to operationally sized vehicles. Additional underground nuclear tests to establish pulse-unit specific impulse.

High-explosive dynamic tests (nonnuclear) of critical structural elements under conditions which simulate mechanically the impulse delivered to the vehicle by the pulse unit, again at scales relevant to usefully sized vehicles.

Completion of research programs in these areas, possibly within three years, would confirm in considerable detail the performance, structural integrity, and operational reliability of early nuclear pulse vehicles. A strong indication of growth potential would also be ascertained. These data, acquired at modest cost, would provide a sound technical basis for any further course of action.

8. SUGGESTED ADDITIONAL EFFORT

The current technical and programmatic status now supports consideration of additional effort directed toward better understanding both the opportunities and special implica-

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tions of nuclear pulse propulsion in a context responsive to an ever-changing National Space Program. The more pertinent or limiting technical considerations must certainly receive additional attention. In addition, formal effort, primarily by appropriate government agencies, should be concerned with certain policy issues confronting national use of nuclear pulse systems. Specifically, the following areas are suggested as now justifying increased attention.

- *Propulsion Module Design Studies*
  Integrated design studies should be undertaken to provide additional technical support or modifications to the conclusions reached herein. Particular emphasis should be given the Saturn V compatible propulsion modules.
- *Applied Research Programs*
  Analytical and experimental effort in the key technical problem areas should be expanded. Specifically, a series of small, underground, nuclear experiments and HE-driven dynamic response experiments should be initiated.
- *Mission Applications Studies*
  Increased effort should be undertaken to place nuclear pulse propulsion capability more clearly in a mission-oriented framework, to establish operational criteria, to evaluate hazards, to understand better the over-all economic advantages of such space propulsion capability, and to indicate how and when such a capability might best be integrated into the space program.
- *Development Planning*
  A comprehensive development planning effort, with joint participation by government agencies and contractors, should assess in detail the elements of the development plan proposed in this report. Proposed facilities scheduling and time-integration into other elements of the space program should be established. Required resource availabilities, such as boosters, launch facilities, and special nuclear materials, should be specified.
- *Nuclear-source Design*
  The design, fabrication, and testing of the nuclear energy sources in the pulse units fall within the province of the AEC. To date, all project technical studies have considered only nuclear devices currently stockpiled or those with principles well established. However, there is a certainty of achieving substantial improvements in performance and mission economics if the nuclear devices were specifically designed to satisfy nuclear pulse vehicle requirements. It is therefore suggested that the AEC, working closely with the propulsion-system specialists, consider initiation of design studies for this purpose.
- *Nuclear Test Ban*
  Current wording of the Nuclear Test Ban Treaty precludes the final development and/or operation of nuclear pulse vehicles. However, the professed *intent* of the agreement is basically to limit the arms race and to prevent further major contamination of the earth's environment. Nuclear pulse propulsion systems violate neither of these criteria, but their use may be prevented by the wording of the treaty language. Provided a strong mission requirement can be shown for their development, a substantial effort will be needed to advance such arguments clearly so as to obtain the necessary adjustments in the treaty language. It is therefore suggested that, at the appropriate time, a joint study be undertaken to attempt resolution of this issue. Although nuclear testing in space would not in any event be required for some six to eight years, some indication that development could be accommodated is certainly desirable prior to large-scale developmental funding.

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