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NUCLEAR PULSE PROPULSION

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SUMMARY

A general technical description and programmatic review of nuclear pulse propulsion activities over the last decade is presented. Major problem areas are reviewed together with the status of current research efforts. Sufficient technical information is now available to predict achievable propulsion systems performance with a rather high degree of confidence based on current materials and nuclear technology. Expected performance is summarized for one specific small propulsion module capable of being orbited by a Saturn V ELV. Finally, technical routes to achieve substantial performance improvements beyond those currently indicated are discussed.

I. SCIENTIFIC RATIONALE

Interest in employing nuclear explosives to provide a basic energy source for high-performance space engines dates from the late 1940's to middle 1950's when early exploratory calculations were performed at the Los Alamos Scientific Laboratory. In the late 1950's interest became intensified, and analytical and experimental studies of the basic physical and engineering problems involved in a specific form of the concept have been under way continuously since that time.

In these days of the nuclear test-ban treaties and with hopeful general easing of world tension, one might well ask why interest in employing nuclear explosives in such a manner has persisted. Motivation for employing nuclear explosives in the past has been primarily to destroy the works of man, and everyone is impressed with the highly effective way these ends have been achieved. But the use of nuclear explosives as a source of propulsion energy appears at first to be difficult, and perhaps even bizarre. Once a prominent space official was asked before a briefing what his impression was of nuclear pulse propulsion. "Well," he replied, "you set off one big bomb and the whole shebang blows up."

Those who are enthusiastic about the possibilities of nondestructive propulsive use of explosives are so because of two fundamental and very compelling reasons: First, there is no more compact energy source known to man than that provided by nuclear explosives. They are capable of generating enormous Btu's per pound, resulting in extremely high particle (or propellant) velocities, which are, in the extreme, limited only by the disassembly velocity of the explosive. If "energy" were the only consideration, specific impulses well in excess of 200,000 sec could now be contemplated. Currently, however, there are no good ideas on how to handle the velocities involved with any sensible propulsion system—we are utilizing only a few percent of the velocities available to us. Second, and of more immediate interest, the impulsive application of the energy source provides a means of circumventing the thermal barriers inherent in other nuclear systems.

All steady-state nuclear propulsion systems now being developed or seriously contemplated are limited in performance by allowable temperatures in the engine structure. Performance, or I_{sp}, increases as $\sqrt{T}$, other things remaining equal. For example, solid-core nuclear rockets contain fuel elements which must remain structurally intact at temperatures in excess of the maximum propellant temperatures. This means propellant temperatures can probably never exceed 4,000° K. Gas-core systems attempt to "trick" the engine structure by insulating it from the high-temperature fissioning energy source by means of a gas which, upon heating, becomes the propellant. If this method should work, a considerable improvement in exhaust temperatures can be expected.

The nuclear pulse propulsion system is another approach. Early calculations indicated that by reducing the engine "operating" times (or, in other words, the time during which the propellant created by each explosion interacts with the engine structure) to a millisecond or less, useful momentum could be transferred although thermal waves would not have time to penetrate the engine structure. An old analogy here is that of flicking a hot coal off a rug back into the fireplace (impulsive system). If done adroitly, the interaction time is insufficient to burn your finger. But if you pick it up and set it in the fireplace, it is a different study (steady-state system). Note that the same payload is carried through the same velocity increment in both cases.

Experiments to date confirm that common materials such as aluminum or steel can withstand surface temperatures of over 80,000° K for short time periods with only nominal ablation of the surface.

II. CLASSES OF NUCLEAR-PULSE ENGINES

Two distinct variations of nuclear pulse propulsion engines have been under formal study in the United States. Figure 1 indicates schematically each system. The first system provides almost complete containment of the explosive by means of a strong pressure vessel which absorbs the initial shock wave and then expands the explosion debris (propellant) through a more or less conventional nozzle. Initial studies of this system have been performed by several organizations, including D. Cole of the Martin Company. Essentially all of the products of the explosion are employed as propellant and hence the system's performance is limited primarily by maximum chamber pressures and temperatures which can be tolerated for any given pressure vessel weight. This is analogous to an "internal combustion engine."

The second, or "external combustion engine," differs in that the primary energy source is displaced a distance from the engine structure and some fraction of the expanding explosion debris (propellant) is intercepted by a flat circular structure, or piston, called the pusher plate. Some of the total expended mass is lost and cannot be utilized as propellant. But, as will be pointed out later, by decoupling the energy source from the engine, the constraints imposed by strength of materials are relieved and considerably higher propellant temperatures and velocities can be contemplated before structure heating becomes a deterrent. This second system is more commonly known as the ORION concept. Research on ORION, initiated by Dr. T. B. Taylor of General Atomic Division of General Dynamics Corporation over seven years ago, has been carried forward under ARPA, USAF, NASA, and General Dynamics sponsorship. The remainder of this paper will be limited to a discussion of the current status of the ORION propulsion system.

III. MAJOR TECHNICAL PROBLEM AREAS

Figure 2 indicates in more detail the operating cycle of the ORION engine and identifies the major technical problems which have been under study. A large number of small nuclear explosive devices called pulse units are stored within the vehicle. They are sequentially ejected and detonated external to and some distance below the engine. Upon striking the pusher, the momentum of the expanding debris (propellant) in the form of a high-velocity, high-density plasma is transferred to the pusher and the resulting large accelerations are smoothed out by shock-absorbing devices to levels of a few g's in the upper vehicle—well within human tolerance. After compressing the shock absorbers, the pusher returns to its neutral position and is ready to accept the following impulse in times of typically one to two seconds. Any desired total vehicle velocity is acquired by varying the total number of pulse units expended. The propellant/pusher interaction times range under one millisecond. Therefore, the total "operating time" of propellant interaction for even a high mission velocity may be under one second.

During each interaction the propellant creates ablating conditions in a very thin region on the bottom surface of the pusher. A great deal of effort has been directed toward understanding the mechanisms of ablation, how it varies with propellant conditions and pusher materials, and predicting quantitatively what its effect will be for realistic designs. Performance is influenced by the amount of mass lost by the ablation process and it represents a key problem area. As mentioned earlier, however, thermal conditions are constrained to the pusher surface and little bulk heating of the plate itself will accrue.

During the interaction, large pressures are created by the propellant which, in turn, impart high accelerations to the pusher. A second and somewhat interrelated problem area then is the determination of the maximum mechanical impulse which can be structurally tolerated by a pusher-shock absorber combination that is practical engineeringwise. The overall problem is one of achieving a balance or trade-off between constraints imposed by the energy source, the thermal pusher ablation, and the structure which must be provided to transmit useful velocity increments to the manned payload.

An important point and one frequently misunderstood is that for propulsive purposes we are ultimately interested in total momentum imparted to a vehicle with as little internal energy increase as possible. In the case of ORION the internal (heat) energy transfer to the pusher is only a small fraction of the total energy available. This very important characteristic permits maintaining the major engine components at operating temperatures low enough so that common construction materials such as steel, titanium, organic fibers, and elastomers may be used.

Another important characteristic of ORION is that the system is noncryogenic; the stored "propellant" is composed of dense and rugged solid capsules, implying small tankage fractions and ease of handling and transfer in space. Furthermore, because of the remoteness of the energy source from the engine proper, nuclear radiation levels in the structure are low enough so that nuclear heating effects are relatively unimportant. There is, of course, no significant after-heat consideration. Shutdown activation levels should not preclude manned access to any portion of the engine for inspection, repairs, or docking assist very shortly after operation.

Internal engine controls and integral operation of the various subsystems in the required time sequence are expected to present some formidable problems. However, although difficult, solutions appear to be straightforward and no major new technology should be required. Vehicle thrust vector control—which is provided by variable thrust chemical motors—again is a problem area which does not appear to affect basic system feasibility or performance.

IV. TECHNICAL STATUS

Research efforts over the past seven years have been largely concentrated on determining the behavior of the nuclear pulse unit, obtaining quantitative descriptions of ablation, and determining mechanical constraints imposed by the engine structure. A substantial fraction of the effort has gone into developing predictive techniques, digital computer programs, and models which have then been checked against experiments whenever possible and modified as required. About half of the total program effort to date has been experimental and half analytical.

Figure 3 is a schematic of the basic experimental tool employed in the ablation research program. It is a high-energy-density plasma generator employing a high-explosive implosion source. The resulting plasma is permitted to expand into an evacuated chamber and to strike a target. By means of instrumentation in or near the target, plasma parameters such as density, pressure, velocity, and temperature are determined and resulting ablation of the target sample is measured as a function of time. Figure 4 shows a typical aluminum ablation sample after exposure; one side of the plate was "shielded" from the stagnating plasma while the other was left bare. This technique has been extensively used to confirm theoretical predictions of ablation under achievable experimental conditions. However, additional experimental confirmation is needed before the ablation problem can be considered adequately resolved.

Figure 5 shows a mechanical impulse generator that has been developed on the project to simulate the hydrodynamic pressure-time and pressure-radius conditions created at the propellant-pusher interface. This technique employs sheet high explosive to drive a hydrodynamic impulse into pusher samples. Repetitive experiments may be performed to study possible fatigue problems. It has been used to experimentally confirm dynamic response calculations and to establish allowable limits of pressure and acceleration on candidate pusher, shock absorber, and shock-absorber attachment systems. Experiments have mainly been on scaled samples as shown; however, the technique appears applicable for use with up to full-scale components and modules.

V. RESULTS OF REFERENCE ENGINE DESIGN STUDIES

In parallel with the research programs described above, integrated engine design studies have been carried out to translate results of the technology programs into potential operational systems. In turn, these studies tend to direct the research efforts into areas of highest interest and payoff from an overall propulsion system standpoint. As part of this effort, analysis and preliminary design studies of all major components and subsystems that constitute a meaningful operating engine have been performed and scaling laws derived to determine critical interfaces, to obtain realistic weight estimates, and to delineate areas requiring state-of-art improvements.

The technology efforts are, to first order, independent of engine size; however, to obtain internally self-consistent designs, reference engine systems of fixed sizes have been investigated in some detail.

The results of one such reference design study are shown in Fig. 6, which is of a propulsion module of approximately 200,000 lb gross weight and 33 ft in diameter. This module was selected for compatible lofting to orbit by a two-stage Saturn V vehicle. There is nothing particularly magic about its size, and modules of both larger and smaller gross weights appear feasible. The thrust-to-weight ratios of such modules are expected to be somewhere between one and six. This is not quite analogous to thrust-to-weight ratios of chemical engines, as it includes all pulse unit handling and delivery apparatus, engine controls, apparatus for attachment of fuel magazines, and auxiliary subsystems and spares. The predicted specific impulse is calculated to be between 1,800 and 2,500 sec, which results in characteristic single-stage velocities of about 100,000 ft/sec.

If performance of this class is achievable, and this may well represent a first generation, rather modest goal for nuclear pulse systems, vehicles utilizing such an engine and operating from earth orbit could typically deliver 45% of their gross weight as useful payload to the lunar surface, over 40% to the Mars surface, and could carry in excess of 25% in a fast, manned, round-trip to Mars permitting landings and exploration of the Mars surface.

VI. POSSIBILITIES FOR PERFORMANCE IMPROVEMENTS

An obvious and direct approach to improved performance is to simply use a larger propulsion system. No basic technology improvements are involved. Thrust-to-weight ratios remain more or less constant with increasing size, but the I_{sp} increases significantly as the pusher diameter increases. Current estimates are that growth in I_{sp} upward to perhaps a factor of three might be achieved with increasing propulsion system size.

A second type of improvement would be derived from the use of advanced high-strength materials in the pusher or shock absorbers. Current designs have been restricted to "handbook" materials. The use of advanced materials would permit increased allowable pressures, resulting in both improved I_{sp} and higher engine thrust-to-weight ratios.

The most thought-provoking approach may derive simply from advancements in our current knowledge of the energy transport mechanisms involved. As noted in the beginning, we certainly are not energy poor. Our lack of understanding of basic ablation processes applies constraints to current design thinking which cannot be violated without a decrease in confidence. As more experience is gained, these barriers could become more imaginary than real, permitting really substantial improvements in performance over that now indicated. On the other hand, nature may conspire against us when we try to push her. There is simply not sufficient information available at this time. However, definitive experiments to explore these phenomena in the appropriate regions have been designed and could in a very few years produce the information needed. These milestones, when achieved, could well provide the scientific basis upon which a new generation of truly high-performance space engines capable of operation throughout the solar system is founded.

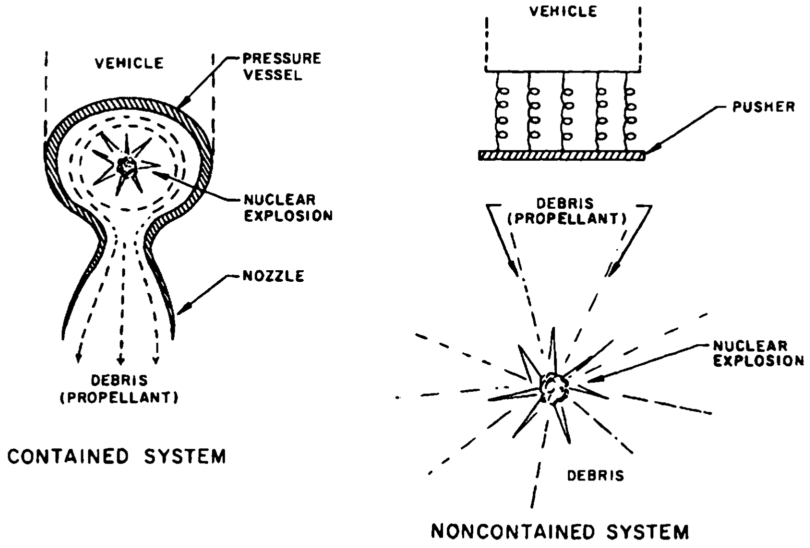

Fig. 1—Classes of nuclear pulse engines.

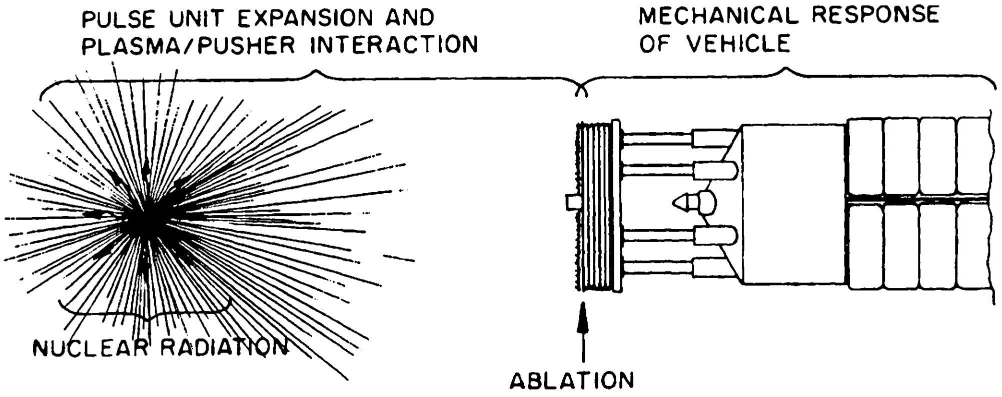

Fig. 2—Separability of nuclear pulse problems.

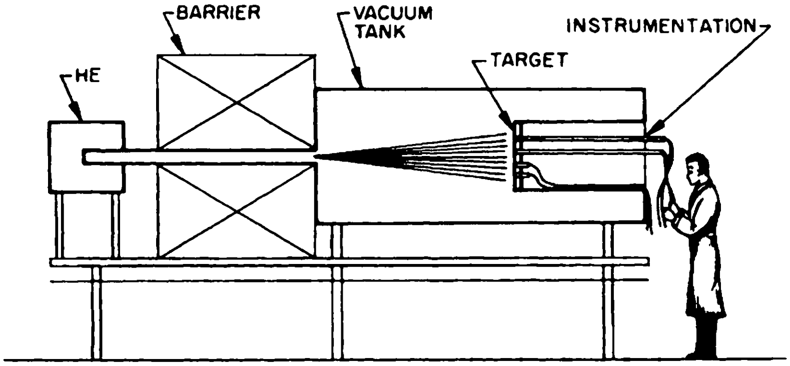

Fig. 3—HE Plasma generator—Ablation experiment.

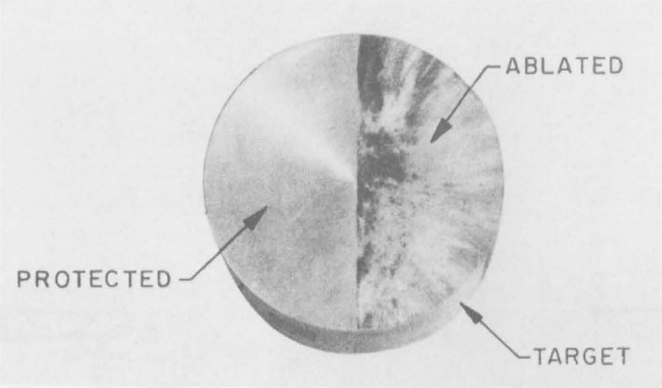

Fig. 4—Typical pusher ablation sample.

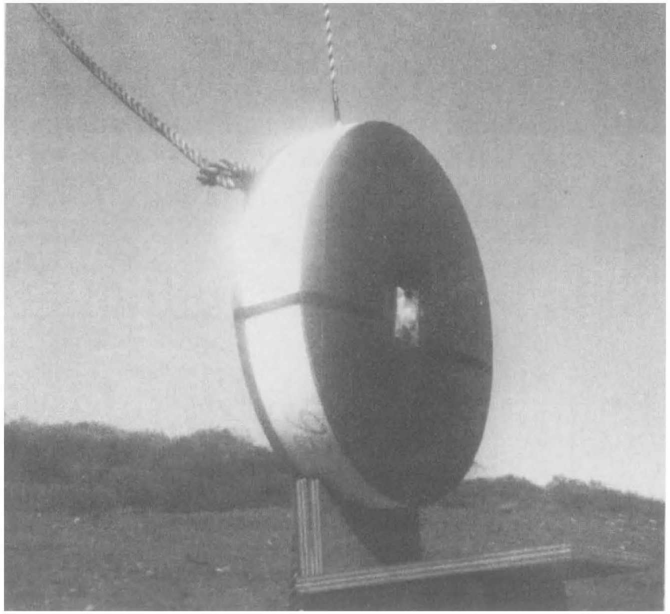

Fig. 5—Typical pusher impulse experiment.

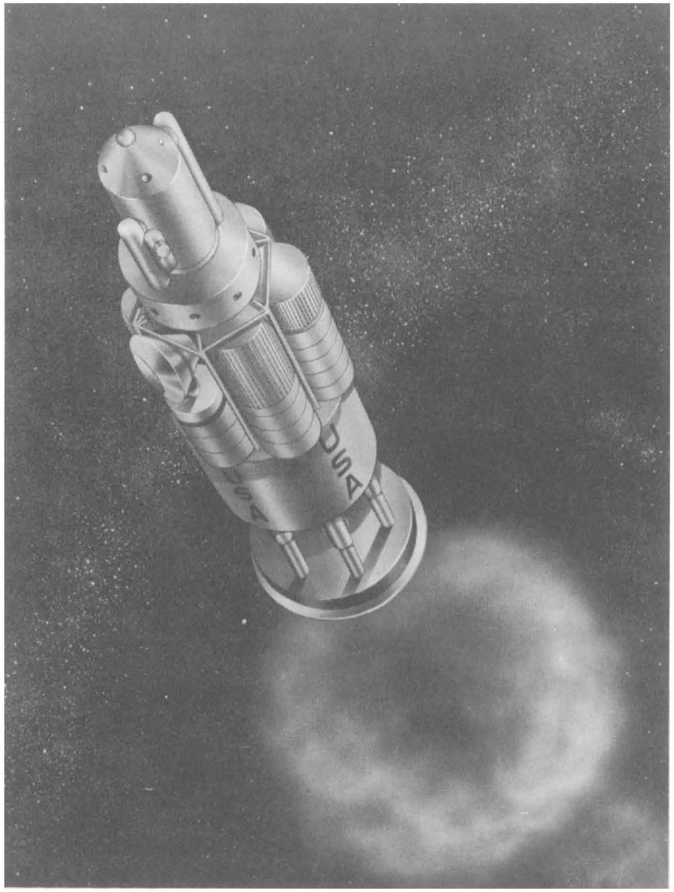

Fig. 6—Nuclear pulse vehicle.