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Project Orion and Future Prospects for Nuclear Pulse Propulsion

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The race to the Moon dominated human space flight during the 1960s and culminated in Project Apollo, which placed 12 men on the lunar surface. Unbeknownst to the public at that time, several U.S. government agencies sponsored another project that could have conceivably placed large bases on the moon and eventually sent crewed expeditions to Mars and the outer planets within the same period of time as Apollo, and for approximately the same cost. The project, code-named Orion, featured an extraordinary propulsion method known as nuclear pulse propulsion. First conceived at the dawn of the space age, the concept was as radical then as it is now. However, its feasibility was never dismissed on purely technical grounds. In fact, many of the scientists and engineers who came into contact with the program over its seven-year lifetime became convinced of its viability. The political and nontechnical issues that finally sealed the program's fate would certainly make the original Orion unacceptable by today's standards. However, new technologies and ideas developed since then could mitigate some of the major issues, and make nuclear pulse propulsion less unreasonable to consider for future human exploration, at least beyond Mars orbit. These new approaches are presented, following a discussion of the technological rationale for nuclear pulse propulsion and a general history of the concept.

Nomenclature

c_V	=	specific heat, J/kg · K
I_{sp}	=	specific impulse, s
M	=	mass, kg
T	=	temperature, K
t	=	time, s
$U(t)$	=	internal energy, J/kg
α	=	specific power, kW/kg

Introduction

THE 20th century saw tremendous progress in the science and engineering of chemical rockets. These advances ushered in the deployment of satellite systems in Earth orbit, the boost of scientific probes into the farthest reaches of the solar system, and the transport of humans to and from the moon. Although these accomplishments have been impressive, chemical rocketry has come very close to reaching the theoretical limits of its performance. Accomplishing the more ambitious goals of establishing human settlements on Mars, conducting rapid interplanetary space flight throughout the solar system, and eventually travelling to the stars will require new, high-performance propulsion systems based on nonchemical energy sources.

As always, cost is a principal factor driving the need for systems with much greater performance. However, when considering transportation of human crews over distances of billions of kilometers, safety becomes an equal if not more important concern. The principal safety issues stem from the adverse effects on human physiology caused by prolonged exposure to microgravity and the severe radiation environment of space, and from the psychological stress induced by long periods of isolation.

From the standpoint of propulsion and spacecraft design, these problems can be solved in two ways. One is to add design features and equipment that reduce the health risk of long-duration space missions. These include countermeasures, such as artificial gravity and health maintenance programs, and enhancements, such as added radiation protection, power, living space, and subsystem redundancy. Unfortunately, such features generally lead to substantially larger and heavier spacecraft, which ultimately cost more to launch into Earth orbit.

Another more straightforward remedy is to cut trip time by travelling at very high-energy, hyperbolic trajectories. This approach demands propulsion systems that can deliver far greater exhaust momentum per unit mass I_{sp} than modern-day chemical rockets and that can operate at significantly larger specific powers α than current high-performance electric propulsion systems. Many advanced propulsion concepts have been identified that could, at least theoretically, meet these needs. The only problem is that virtually all of these technologies, such as fusion, antimatter, and beamed energy, have fundamental scientific issues and practical weaknesses that must be resolved before they can be seriously considered for actual applications.

For instance, pure fusion is limited because research in this area is still far away from demonstrating a nonfission-driven fusion device having energy gains sufficient for space applications, let alone commercial power.[1] Antimatter, although appealing due to its high specific energy, is severely hampered by extremely low propulsion efficiencies and the high costs of present-day antimatter production methods.[2] Beamed energy offers great potential, too, but requires power conversion processes far beyond current state of the art and a tremendous investment in power-beaming infrastructure.

Undoubtedly, many of these issues will be overcome, but there is no guarantee that systems based on these technologies could be successfully fielded any time soon. This state of affairs points to the disappointing fact that none of the familiar advanced, high-α propulsion concepts could, with any degree of certainty, meet the vision of enabling human space flight throughout the solar system within this century. This is especially true in light of the conservative fiscal environment of the post-Cold War era, which could limit the sizable investment needed to resolve the fundamental issues associated with these concepts. Developing actual vehicles based on these technologies and their required infrastructure could realistically cost on the order of hundreds of billions of dollars.

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The rather bleak prospects for near-term high-I_{sp}/high-α propulsion improve, however, when we reconsider an unusual method that grew out of nuclear weapons research during World War II. This concept, nuclear pulse propulsion (NPP), represents a radical departure from conventional approaches in that it utilizes the highly energetic and efficient energy release from nuclear explosions to produce thrust.

At first it would seem ridiculous to think that anything could survive the hundreds of thousand degree temperatures at the periphery of a nuclear explosion, much less than the multimillion degree temperatures at the core. However, as nuclear research advanced in the 1950s and 1960s, it became apparent that some materials under special conditions could survive a nuclear detonation and survive it well enough to provide a controllable conversion of blast energy into vehicle kinetic energy. Most intriguing of all is that this approach could deliver I_{sp} between 5,000 and 10,000 s and up to 50,000 s with average thrust-to-mass ratios equal to or greater than chemical rockets, using existing technology.

The bulk of this work occurred under the Orion program, a seven-year project sponsored by the U.S. government from 1958 to 1965. It is impossible to think that the Orion spacecraft envisioned back then would be acceptable by today's political and environmental standards. However, the program does provide a starting point for presenting some new ideas on NPP, which could achieve not only better performance than the original concepts but could mitigate many of the issues associated with nuclear proliferation, environment contamination, and costly deployment in space.

Origin of the Concept

The idea of using a series of explosive pulses to propel a rocket vehicle can be traced back to Hermann Ganswindt, who published his ideas in the 1890s, and R. B. Gostkowski, who issued the first scientific study of a concept using dynamite charges in 1900 (see Ref. 3). These studies identified the two main issues in attaining high I_{sp} with this type of system. First is the energy per unit mass or specific yield of the detonations. The effective exhaust velocity and I_{sp} are proportional to the square root of the energy distributed over the entire mass of the explosive charge and point to the need to achieve as high of specific yield as possible. The second consideration is designing the vehicle to cope with the mechanical and thermal effects of the blast, which places a maximum limit on the utilizable energy.

The next significant step was the idea of using an explosive charge with much greater specific energy than dynamite, namely, the atomic bomb. In contrast with chemical explosives, the specific energies of nuclear reactions are so high that mission performance is limited by vehicle design constraints, rather than energy content of the fuel. Completely fissioning 0.057 kg of fissionable material produces 4.18×10^{12} J of energy. This is equivalent to the available in explosive energy 1000 short tons (1 kiloton or 1 kton) of TNT, and is roughly seven orders of magnitude greater than combusting an equivalent mass of oxygen and hydrogen.[4] Distributing this directly over the mass yields a maximum theoretical I_{sp} of $\sim 1.3 \times 10^6$ s.

However, in the initially high-density plasma of a nuclear explosive, the kinetic energy of the fission fragments, which have mean free paths on the order of millimeters, is completely dissipated through coulombic interactions. In addition, electrons quickly decelerate and create photons, which react with other free electrons and remaining bound electrons. The processes take place over a timescale of nanoseconds, and the system is in a state of thermodynamic equilibrium. Thus, its internal energy U, a measure of the microscopic random motion created by the transfer of prompt fission energy as heat, consists of the following two terms[5]:

$$U = Mc_V T + CT^4 \tag{1}$$

where C is a constant. During early generations of supercriticality, the first term of Eq. (1) is dominant. However, in later generations, the temperatures are so large that the fissioning plasma essentially becomes a blackbody radiator. For a 2–3 keV blackbody with temperatures ranging from 10^6 to 10^7 K, most of the energy is manifested in the form of x-rays. The coupling between pulse energy and vehicle kinetic energy depends on which term in Eq. (1) is dominant.

Fusion explosions also produce large amounts of energy. Because the binding energy per nucleon of fusion fuels is much lower than fissile materials such as uranium and plutonium, the specific energy or 100% burn yields per kilogram are higher than that of fission. The product kinetic energy from fusion of deuterium and helium-3 yields a theoretical I_{sp} that is nearly twice as great, $\sim 2.2 \times 10^6$ s. Furthermore, because of the lower typical densities at fusion ignition, the plasma remains out of thermodynamic equilibrium and loses a smaller fraction of its energy to radiant heat.

Stanislaus Ulam outlined the first proposal for use of fission-based explosives in 1946, followed by some preliminary calculations by F. Reines and Ulam in 1947. The first full mathematical treatment of the concept was published by Everett and Ulam in 1955 (Ref. 6). The U.S. Atomic Energy Commission was awarded a patent for the concept, termed "external nuclear pulse method," following initial application in 1959 (Ref. 7).

The earliest physical demonstration and proof of the concept's merit occurred in an experiment conceived by physicist Lew Allen. Code-named Viper, the test was conducted at the Eniwetok Island nuclear facility in the Pacific Ocean and involved detonating a 20-kton nuclear device 10 m away from two $\sim$1-m-diam graphite-coated steel spheres. The wires holding the spheres were vaporized immediately, but not so for the spheres themselves. Some time later and several kilometers from ground zero, the spheres were recovered, with only a few thousandths of an inch of graphite ablated from their surfaces.[3,8] Most important, their interiors were completely unscathed.

Types of Concepts

The two basic types of nuclear pulse concepts that have been examined over the years are shown schematically in Fig. 1 (Ref. 3). Both concepts share many common features and differ primarily in how energy from the nuclear explosion is converted into vehicle kinetic energy. In either case, a number of nuclear pulse units are ejected and detonated successively at a predetermined location relative to the vehicle.

External NPP

The external NPP concept was historically the first to be conceived. The pulse takes place externally at some distance from a pusher plate attached to the vehicle. For a nuclear device of typical yield, thrust is produced through the initial impingement of nearly instantaneous x-rays emanating from the plasma fireball, followed by blast energy from the expanding shell of plasma and ionized debris.

The x-ray mode deposits energy directly on the plate, which ablates some of the plate's surface. More importantly, this radiation forms a shock wave that propagates into the plate's interior and

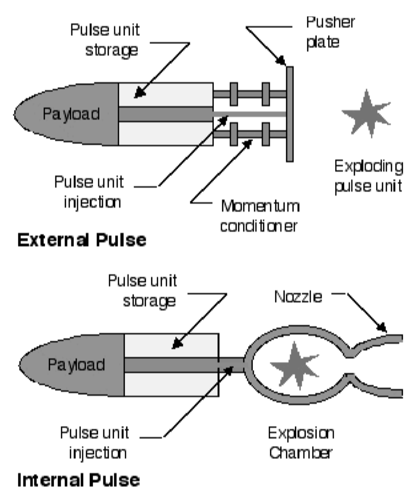

Fig. 1 NPP Concepts.

reflects back to the surface. This energy exchange expends mass and produces thrust through both ablation and spallation from the reflected shock. The blast mode transfers momentum directly to the vehicle. The stagnation of the expanding plasma shell against the plate forms an intense normal shock with peak temperatures of millions of degrees. Although this causes severe thermal loading to the plate surface for a few milliseconds, a protective layer of opaque gas, formed by either the radiation-induced ablation or subsequent plasma impingement, keeps erosion within acceptable levels.

Normally, the x-ray mode becomes more dominant as the pulse unit's specific yield is increased due to the higher burnup fraction and temperature. Because this causes extreme stresses within the plate, previous studies determined it best to convert this radiation to plasma kinetic energy and to rely on the blast mode of momentum exchange. These studies added material in the vehicle-facing part of the pulse unit to absorb x-ray energy and convert it into more tractable plasma kinetic energy. Heavier material added to the other end of the device (shape charging) further directionalized the pulse energy into the plasma that impinged on the vehicle. Although incorporation of additional material lowers the effective specific yield and I_{sp}, it provides a less severe environment on the plate's surface and yields the best overall vehicle performance.

Regardless of the partitioning between plasma kinetic energy and x-ray energy, a springlike conditioning unit provides a nearly constant acceleration by smoothing out the momentum transfer between pulses and returns the plate to its proper location for the next pulse. The pulses are ejected and detonated at a frequency that causes the plate to oscillate harmonically. This minimizes dissipative losses and maximizes coupling between the vehicle and blast energy.

The advantage of external NPP is that no attempt is made to confine the explosion. Thus, it circumvents the material temperature and pressure limits associated with confined concepts, such as solid- and gas-core nuclear thermal rockets. The interaction time of the propellant with the vehicle is so short that essentially no heat transfer occurs. The temperatures in the propellant cloud may be $\sim 10^6$ K, but because the interaction time can be as low as ~ 0.1 ms, only a small amount of surface material is ablated and lost. This pulsed nature is essential to the concept's feasibility, because if such high temperatures were applied for any extended length of time, the vehicle would be destroyed.

The I_{sp} attainable with the external concept is proportional to the product of the propellant impingement velocity perpendicular to the pusher plate and the fraction of pulse unit mass striking it. The impingement velocity is limited by pusher plate ablation, and is probably in the range of 100–200 km/s. The pulse unit mass fraction is determined by design of the explosive charge and the standoff distance, and is in the range of 10–50%. The resulting I_{sp} limits are approximately 3,000–10,000 s (Ref. 9).

External NPP with Pusher Plate/Magnetic Field

The limits on I_{sp} due to ablation and spallation can be overcome by using a magnetic field to shield the surface from the high-energy plasma. Magnetic field lines are generated parallel to the surface of a conducting pusher plate. As the plasma from the explosion expands, it pushes the field lines against the conductor, increasing flux density. The increased magnetic pressure slows down the plasma and brings its axial velocity component to zero. The potential energy in the field then produces thrust by accelerating the plasma in the opposite direction, away from the pusher plate. Because the impulse is transferred to the vehicle by magnetic interactions, the plate's surface is buffered from particle impingement, and the propellant particle energies and I_{sp} can be higher than those with an unshielded plate.

Magnetic shielding was first mentioned by Everett and Ulam (see Ref. 3), and the feature has become a virtual standard on the high-power fusion pulse vehicle studies since Orion. Note that plasma confinement using magnetic fields is not perfect, and any high-temperature neutral particles will be unaffected. However, the few neutral particles that are present would experience mild deceleration due to physical interaction with the more populous charged particles. In general, magnetic shielding offers the only method of attaining I_{sp} of 50,000 s and above. However, it would be difficult to attain I_{sp} beyond 50,000 s because, at this point, most of the pulse unit energy is lost to thermal radiation.

Internal NPP

In the internal NPP concept, the explosion takes place inside a pressure vessel from which heated propellant is expanded through a conventional nozzle. When this method was conceived, it was supposed that use of an enclosed reaction chamber and nozzle would eliminate the energy losses associated with isotropic external expansion and lead to greater performance.

Propellant (liquid hydrogen or water) is fed into the pressure vessel radially through the wall and serves as a coolant. The explosion occurs at the center of the vessel, propagating a shock wave through the propellant until it is reflected from the walls. This wave is reflected back and forth in the vessel, increasing the internal energy of the hydrogen until equilibrium is established. Heating and expansion through the nozzle takes a few milliseconds, after which the vessel is replenished with additional propellant, and the cycle is repeated.

One of the main limitations to the performance of an internal system is radiation heating, which arises from the x-rays, γ-rays, and neutrons deposited into the chamber wall. Even with highly efficient pulses, the large amount of fluid/propellant required to keep the chamber within reasonable temperatures restricts I_{sp} to less than 1500 s, at least an order of magnitude lower than that of an external system with the same pulse unit mass.[10]

The other limiting factor is the greater mass of internal NPP vehicles. Studies showed that the minimum mass of an external system will always be less than that for an internal system for the same payload and mission, and that I_{sp} greater than 1400 s will require very heavy engines.[10]

Project Orion

The most extensive effort on fission-based NPP was performed in Project Orion.[3] Apart from the valid political and environmental concerns that would prevent development of such a system today, the Orion project did obtain some interesting results. It is worthwhile to examine these now, especially in light of the serious technological obstacles posed by some of the other advanced propulsion concepts being researched for ambitious human space flight.

Beginning (1957–1958)

Project Orion began in 1958 at the General Atomic Division of General Dynamics in San Diego, California. The originator and driving force behind the project was Theodore Taylor, a former weapons designer at Los Alamos National Laboratory, who sought a nuclear propulsion system that would regain American prestige in space in the wake of Sputnik.

Taylor had encountered the NPP concept at Los Alamos. Being an expert at making small bombs at a time when the drive was toward high-yield weapons, Taylor conceived a system in which the propellant mass was incorporated along with the nuclear charge in simple pulse units, rather than the cumbersome separate disk/charge arrangement in Ulam's original proposal. Taylor adopted Ulam's pusher-plate idea, but instead of propellant disks, he combined propellant and nuclear charge into a single pulse unit.

Taylor and Francis de Hoffman, the founder of General Atomic, persuaded Freeman Dyson, a theoretical physicist at Princeton's Institute for Advanced Study, to come to San Diego to work on Orion during the 1958–1959 academic year. Taylor and Dyson were convinced that the approach to space flight being pursued by NASA was deficient. In their opinion, chemical rockets were too expensive, had very limited payload capability, and were essentially useless for flights beyond the moon. The Orion team aimed for a spaceship that was simple, rugged, roomy, and affordable. Taylor originally called for a ground launch, probably from the U.S. nuclear test site in Nevada. The vehicle, which is shown in Fig. 2, looked like a bullet, was ~ 80 m high, and had a pusher plate ~ 40-m in diameter. Analyses showed that a larger pusher plate yielded better performance.

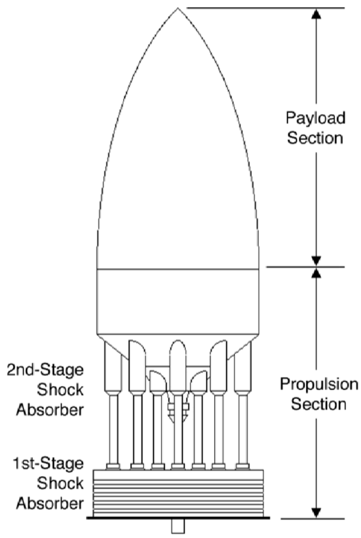

Fig. 2 Early Orion concept.

The mass of the vehicle at liftoff would have been on the order of 10,000 t, most of which would have gone into orbit. During the early phases of ascent, the 0.1-kton-yield pulse units would be ejected at a frequency of one per second. As the vehicle accelerated, the rate would slow down, and the yield would increase to 20-kton pulses detonated every 10 s. The vehicle would fly straight up until it cleared the atmosphere so as to minimize radioactive contamination.

Taylor and Dyson began developing plans for human exploration through much of the solar system. The original Orion design called for 2000 pulse units, far more than the number necessary to attain Earth escape velocity. Their bold vision was evident in the motto embraced at the time, "Mars by 1965, Saturn by 1970." They claimed that up to 150 people could have lived aboard in relative comfort, and the useful payload would have been measured in thousands of tonnes. Orion would have been built with the robustness of a seagoing vessel, not requiring the excruciating weight-saving measures needed for chemically propelled spacecraft.

The cost of fielding a flight-operational system was estimated to be $100 million per year for a 12-year development program. However, this estimate does not include development costs for the thousands of smaller items that such a program would require, such as spacesuits and scientific instruments. Still, even if this estimate was off by a factor of 20, the revised total would have been $24 billion, roughly the same cost as the Apollo program.

Advanced Research Projects Agency Years (1958–1960)

The Orion team realized early on that the U.S. government had to become involved if the project was to have any chance of progressing beyond the research stage. In April 1958, Taylor gave a presentation to the Advanced Research Project Agency (ARPA) of the Department of Defense. The following July, after a good deal of negotiation, an award of $1 million was made to cover 10 months of work. It was at this time that the code name of Orion was assigned.

Shortly after the start of the project, NASA was formed and took over all of the civil space projects funded by ARPA, while the U.S. Air Force inherited all military projects. Orion remained the only major project under ARPA charge because neither NASA nor the Air Force regarded it as a valuable asset. Taylor's efforts to interest NASA at this stage failed, which is difficult to understand in light of the growing interest in going to the moon.

At the end of 1958 an award of $400,000 was made to the project, and in August 1959 another million dollars was placed at the program's disposal to cover the following year's work. The team grew to about 40 members, with the overall project responsibility falling to Frederic de Hoffman. Taylor was appointed project director with James Nance as assistant director. (Nance later took over as director when Taylor left the project in 1963.)

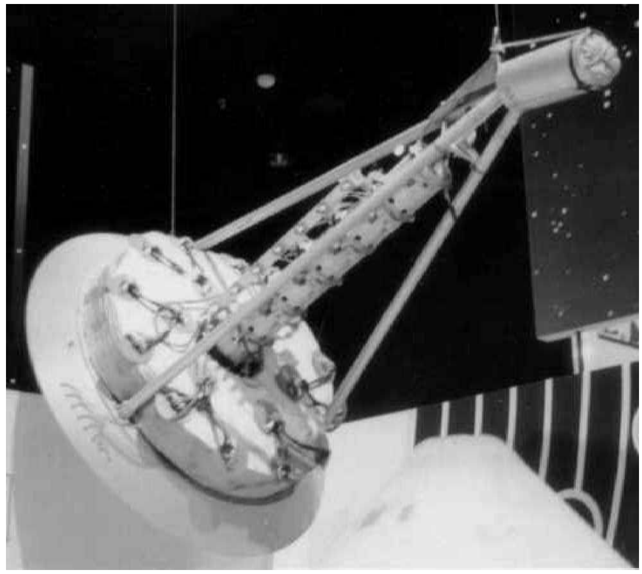

Fig. 3 Putt–Putt flight model.

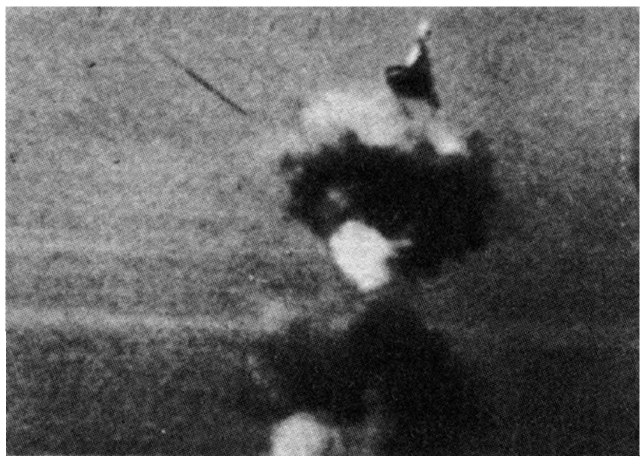

Fig. 4 Putt–Putt flight test.

At this time, the Orion team built a series of flight models, called Putt–Putts, to test inherent flight stability during pulse-mode operation and to determine whether pusher plates made of aluminum could survive the momentary intense temperatures and pressures created by chemical explosives. Figure 3 shows a photograph of one of these models on display in the National Air and Space Museum in Washington, DC. A 100-m flight in November 1959 (Fig. 4), propelled by six charges, successfully demonstrated that impulsive flight could be stable. These experiments also proved that the plate should be thick in the middle and tapered toward the edges to maximize its strength-to-weight ratio.

The durability of the plate was a major issue. The expanding plasma of each nuclear explosion could have a temperature of several tens of thousands of Kelvin even when the explosion occurred hundreds of feet from the plate. Following the lead of the Eniwetok tests, a scheme was devised to spray graphite-based grease onto the plate between blasts. Extensive work was done on plate erosion using an explosive-driven helium plasma generator. The experimenters found that the plate would be exposed to extreme temperatures for only about 1 ms during each explosion and that the ablation would occur only within a thin surface layer of the plate. The duration of high temperatures was so short that very little heat flowed into the plate, and active cooling was unnecessary. The experimenters concluded that either steel or titanium would be durable enough to act as a plate material.

Air Force Years (1960–1963)

A juncture came in late 1959, when ARPA decided it could no longer support Orion on national security grounds. Taylor had no choice but to approach the Air Force for funds. Although it was difficult to sell, the Air Force finally decided to pick up Orion, but only on the condition that a military use be found for it. Taylor's Air Force contacts were sympathetic to the aim of space exploration, but felt that it was outside their purview.

The plan was to use Orion as a weapons platform in polar orbit that could pass over every point on Earth's surface. It could also protect itself easily against attacks by small numbers of missiles. However, this idea had the same disadvantages as the early bomb-carrying satellite proposals. Terminal guidance would have been a problem because the technology for accurately steering warheads had not yet been developed. Furthermore, both the United States and the Soviet Union were deploying missiles that were capable of reaching their targets in 15 min with multimegaton warheads, making orbiting platforms irrelevant.

Little firm information is openly available, but it appears that the vehicles were intended for two types of missions. One role was as a launcher capable of delivering 900-t payloads into low Earth orbit, whereas the other was as an orbiting military platform capable of maneuvering away from threatening missiles launched from Earth and returning to its operating position. The vehicle was most likely propelled by small yield explosions of about 0.01 kton, released from the vehicle at 10-s intervals and detonated between 30 and 300 m behind the pusher plate. The gross launch weight of the basic vehicle was quoted as 3630 tonnes, and the acceleration ranged from 20 to 90 m/s^2. The I_{sp} of 4000–6000 s, along with an average vehicle acceleration of $\geq 1.25\ g$ would enable direct launch from the Earth's surface or suborbital startup. Such vehicles would have a propulsion module inert mass fraction of 0.3–0.4 and pulsing intervals of about 1 s.

NASA Years (1963–1965)

Robert McNamara, Defense Secretary under the Kennedy administration, felt that Orion was not a military asset. His department consistently rejected any increase in funding for the project, which effectively limited it to a feasibility study. Taylor and Dyson knew that another sponsor had to be found if a flight system was ever to be built, and NASA was the only remaining option. Accordingly, Taylor and Nance made at least two trips to NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama.

At this time, Werner Von Braun and his MSFC engineers were developing the Saturn moon rocket. Consequently, the Orion team produced a new, first-generation concept that abandoned ground launch and boosted into orbit as a Saturn V upper stage. A schematic of the vehicle is shown in Fig. 5.

The core of the vehicle was a ~100,000-kg propulsion module with a 10-m-diam pusher plate, which was set by the Saturn diameter envelope. This rather small diameter restricted I_{sp} to 1800 to 2500 s. Although extremely low by NPP standards, this range was 2–3 times that of the NERVA (Nuclear Engine for Rocket Vehicle Application) technology being developed by NASA at that time. The shock absorber system had two sections: a primary unit made up of toroidal pneumatic bags located directly behind the pusher plate and a secondary unit of four telescoping shocks connecting the pusher plate assembly to the rest of the spacecraft.

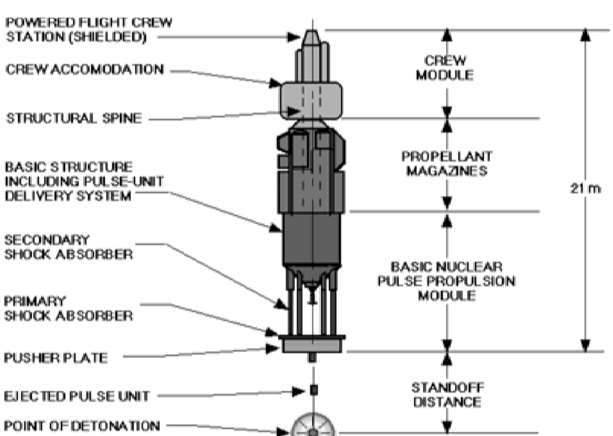

Fig. 5 NASA version Orion spacecraft.

Two or possibly three Saturn Vs would have been required to put this vehicle into orbit, along with some orbital assembly. Several mission profiles were considered. The one developed in greatest detail was for a Mars mission. Eight astronauts, with 100 t of equipment and supplies, could have made a round trip to Mars in 125 days (compared to the one- to over two-year trip times envisioned with conventional chemical and nuclear rockets). Another impressive figure is that as much as 45% of the gross vehicle weight in Earth orbit could have been payload. Presumably the flight would have been made when Mars was nearest to the Earth; still, so much energy was available that almost the fastest-possible path between the planets could have been chosen. An assessment at that time placed the development costs at $1.5 billion with the Saturn Vs representing over 50% of the total cost.

Von Braun became an enthusiastic supporter of Orion, but he was unable to make headway for increased support within NASA. Apart from being reluctant to embrace another nuclear-based propulsion technology, NASA management raised some very practical objections. These included questions, such as "What would happen if a Saturn V should explode while carrying a pulse unit-laden Orion propulsion module?" and "Was it possible to guarantee that not a single pulse unit would inadvertently explode or even rupture?" Although NASA never endorsed Orion or considered the technology a strong contender for post-Apollo missions to the Moon and Mars, its Office of Manned Space Flight was sufficiently interested to fund another study.

Orion's Death

A fateful blow was dealt to Orion in August 1963 with the signing of the nuclear test ban treaty. Although the tests required for development of an Orion vehicle were now illegal under international law, it was still possible that an exemption could be granted for programs that were demonstrably peaceful. However, there is no doubt that the treaty greatly diminished Orion's political support. Another problem was that, because Orion was a classified project, very few people in the engineering and scientific communities were aware of its existence. In an attempt to rectify this, Orion's manager, Nance, lobbied the Air Force to declassify at least a broad outline of the work that had been done. Eventually it agreed, and Nance published a brief description of the first-generation vehicle in 1965.[11]

The Air Force, meanwhile, had become impatient with NASA's noncommittal approach and was willing to be a partner only if NASA contributed significant funds. Hard pressed by the demands of Apollo, NASA made a decision in December 1964 and announced that it would not continue to fund Orion. The Air Force responded by withdrawing its support, thus terminating the program.

All told, approximately $11 million had been spent on Orion over nearly seven years. Dyson stressed the importance of the Orion story ". . . because this is the first time in modern history that a major expansion of human technology has been suppressed for political reasons."[12] In retrospect, there were other issues, besides politics, that contributed to its demise. These included: 1) the inherent large size of the vehicle made full-scale tests difficult and costly, 2) the nuclear test ban treaty excluded testing in the atmosphere or in space, 3) the NERVA nuclear rocket provided strong competition, and 4) no specific mission existed that demanded such a high-performance system.

Orion's Legacy

Although Orion employed fission as the mode of energy release, use of fusion was always viewed as the next logical step in the evolution to ever-higher performance. In 1968, Freeman Dyson was the first to propose application of thermonuclear pulse units for the much more ambitious goal of interstellar flight.[13] His rationale was simple: the debris velocity from such sources was in the range of 3,000–30,000 km/s. With a hemispherical pusher plate, mission velocities of 10^3 to 10^4 km/s were possible. But these concepts employed fission to drive the fusion process and were immense in size. The main advantage of fusion is that there is no minimum mass criticality limit. Thus with an alternative driver, fusion detonations can be made very small—on the order of 0.001 kton and lower.

A new era in thinking about NPP began in the late 1960s and early 1970s. Spurred by optimism for applying controlled fusion to commercial power, researchers ignored use of fissile material, and began to focus on igniting small milli-kton fusion microexplosions. In addition to reducing structural mass of the spacecraft, microexplosions promised significantly lower fuel costs because there would be no need for fissile material or elaborate pulse unit structures.

Soon microexplosion designs began to push toward theoretical I_{sp} levels near 10^6 s, implying exhaust velocities near 3% of light velocity. The pusher plate as replaced by a powerful magnetic field, which channel, charged particles into an exhaust at pulse repetition rates of hundreds per second. Converging laser beams, electron beams, or other driver energy sources ignite the fusion pellets by inertially compressing and confining the fuel. Some of the energy of the microexplosions was tapped electromagnetically to provide power for the lasers and the pusher plate magnetic fields in a bootstrap process. These systems clearly had extraordinary design requirements and pushed technological limits. A vehicle propelled by a 10^6-s I_{sp} engine could in theory visit any location within the solar system in a matter of months.

Members of the British Interplanetary Society took up the challenge of fusion microexplosion propulsion and conducted the most elaborate study to date of a robotic interstellar vehicle. From 1973 to 1978, the team of 13 members worked on Project Daedalus, a two-stage fusion microexplosion spacecraft designed to send a scientific payload of 450 t at 12% light speed on a one-way, 50-year fly-through mission to Barnard's star, 5.9 light years away.[14]

The 10^6-s I_{sp} engines used deuterium and helium-3 fusion fuel; the latter component, because of its scarcity, would have to be mined from Jupiter's atmosphere before the flight. Daedulus would accelerate for about four years using 50,000 t of pellets ignited 250 times per second by relativistic electron beams. The total departure mass, fully fueled, was 54,000 t, almost all of which was propellant.

More recent investigations of fusion microexplosions have considered use of laser inertial confinement, with Lawrence Livermore National Laboratory's VISTA concept (see Ref. 15), and use of combined microfission/fusion with an antimatter trigger.[16] Although the driver technology in all of these cases is very different, the approaches all have their roots in the earlier concepts of fusion-based nuclear pulse propulsion.

Reconsidering NPP

Interest in NPP never really died with Orion; it merely evolved into concepts based on what many view as the tamer and more politically acceptable process of nuclear fusion. In retrospect, this shift in interest was probably premature and was encouraged by overly optimistic projections of fusion's viability. We now know that the challenge of achieving significant energy gain with pure fusion is much more difficult than originally envisioned. In fact, fusion for spacecraft applications may be harder to achieve than for commercial power, due to the need for lightweight subsystems and high gain.[1]

When these formidable challenges are recognized, perhaps it is reasonable to take a half-step back and reconsider the use of fission as a principal energy source for nuclear pulse units. There have been many changes in technology over the last 30–40 years. It is possible that systems based on either combined fission/fusion or fission alone could be made safe, affordable, and far better performing than the designs considered in the Orion program.

Perhaps the main reason why NPP should be reexamined is its synergism with concepts for planetary defense against threatening asteroids, comets, and planetary bodies. Of the many approaches that have been studied, nuclear explosives offer one of the most expedient and flexible ways of altering the trajectory of such objects.[17–20] Although the two applications differ markedly in several respects, they also share many fundamental features, such as the need for high-specific yield, application of ablation-induced thrust, and accounting of stagnation and shock pressure limits.

Technical Challenges and Solutions

For the most part, the Orion program proved that NPP based on self-contained fission explosives is technically feasible. It also showed that large, massive vehicles are required to obtain the high I_{sp} needed to make NPP clearly superior to other propulsion technologies. This strong connection between vehicle size and performance burdens the Orion approach with the same weakness as conventional fusion concepts-large size and mass. Apart from obvious environmental and political issues, the practical implementation of fission-based NPP will require new methods for enhancing pulse unit performance or more effective converting pulse unit energy into vehicle momentum. Improvements in either area could lead to smaller vehicles and better performance.

The goal in improving pulse unit performance is to lower yield while maintaining an energy per unit mass comparable to or greater than that considered for Orion. There has undoubtedly been considerable advancement in the design of nuclear explosives over the last 40–50 years. It would seem that the knowledge accrued from making warheads smaller and lighter could be applied to realize much smaller yield detonations. Unfortunately, extremely high pressures are needed to compress small quantities of fissile material to a supercritical configuration. Reducing the mass of fissile material in an effort to lower yield also decreases the inertia of the implosion, thus reducing the specific energy of the pulse. Countering this through additional chemical explosives and implosion energy may increase the burnup fraction, but the enhanced energy output is offset by the additional mass of chemical explosive.

Use of chemical explosives with higher-energy densities would reduce the impact of additional mass and improve specific energy. However, the technology of conventional lightweight explosives appears to be quite mature. There may have been advancements over recent years that could lower the yield of pure fission devices while maintaining high specific energy. But until such advances become known, the promise of boosting performance via enhanced chemical explosives is speculation, at best.

This leaves only a few options for improving performance. One is to maximize efficiency by using very high-yield, megaton-scale devices in a manner that permits reasonable vehicle sizes and mass. Although more efficient reactions yield higher temperatures and more initial energy in the form of x-rays, it is possible that a portion of this energy could be directed optically onto the pusher plate by means of special materials in the pulse unit. A material layer covering the pusher plate could then couple to this radiation via ablation and produce thrust. The same effect could also be accomplished by injecting material in front of the plate to create an absorbing layer that is opaque to x-rays.

Another method for improving pulse unit performance was suggested in the Orion program and involved shape charging the pulse to directionalize its products toward the pusher plate. The best theoretical performance for NPP is obtained when most of the blast energy is carried by the lightest plasma particles moving toward the vehicle. The heavy particles that recoil in the opposite direction carry away a lower portion of the total energy due to the conservation of momentum. I_{sp} can be improved by 30–40% through shape charging and by employing an optimal distribution of light and heavy propellant.

It is also possible to accommodate high-yield pulses via innovative vehicle design. One that was proposed by Solem[21] does away with the pusher plate entirely and substitutes it with a ~2-km-diam spinnaker-type sail. The sail is located at a large, ~1 km, standoff distance from the pulse, which mitigates the extreme pressures incurred from interaction with the blast wave. It also has a much larger surface area than the 10–40-m-diam pusher plates considered for Orion. The impulse from the blast is smoothed out using a winch mechanism to pay out line as the explosion accelerates the spinnaker. The spinnaker is very large to minimize its exposure to radiation, while the tethers are very long to reduce radiation exposure to the crew.

Another option for reducing mass and yield, while maintaining high specific energies, is through combined fission and fusion. Pure high-gain fusion has been extremely difficult to achieve, even in pulsed operation. However, synergistic fission and fusion processes are well characterized and form the basis of most high-yield nuclear explosives. Winterberg[22] has proposed such a process that could be used to obtain small, low-yield microexplosions. In his "autocatalytic fission–fusion" technique, a subcritical shell of U-235 is imploded via chemical explosive onto a magnetized deuterium–tritium (D–T) plasma. After reaching a high temperature, but one lower than ignition conditions, a small number of D–T reactions occur and release high-energy neutrons. These promote additional fast-fission reactions in the fissile shell, which increase the implosion velocity and fusion reaction rate until sustained burning occurs in the D–T plasma. Key to this process is the magnetized D–T core, which greatly reduces thermal losses during compression. The best feature is that there is no need for the massive onboard fusion drivers envisioned for laser or particle-beam-ignited fusion microexplosions.

Although development of low-yield, high-specific energy pulse units would enable design of smaller vehicles, the fact that the units are self-contained raises the specter of weapons proliferation. This is a reasonable concern, but it can be mitigated by making the pulse units less autonomous through use of an onboard driver (such as electron beams, lasers or pulsed currents) to initiate the reaction. For instance, Bond and Bond[23] studied a technique in which electron beams are used to implode fissile targets and achieve much lower yields and higher efficiency. Winterberg[24] has proposed a similar process using a form of combined fission–fusion. The main advantages of these approaches is that the energy required to drive a fission sample to supercriticality and high burnup fractions may be less than that for comparable fusion processes. In addition, if efficient yields can be achieved in the .001-kton range, then magnetic augmentation could be used to improve pusher plate performance, thus enabling I_{sp} of $\sim$50,000 s.

Another area for enhancing performance or decreasing size is to improve the interaction between blast energy and the vehicle. This can be accomplished primarily through advancements in materials. Orion's pusher plate and momentum transfer assemblies were based on 1950's and 1960's technology, and featured common materials, such as steel and titanium. Research over the last 40 years has opened the prospects of advanced carbon structures and lightweight refractory materials. Carbon is particularly attractive, because it is relatively immune to neutron damage and exhibits excellent strength characteristics at high temperatures. Advanced titanium alloys, cermets and various carbides are all new materials that have not been considered in the design of nuclear pulse systems.

Such material advances could greatly reduce vehicle mass and improve the ablation characteristics of the pusher plate assembly. The latter consideration is particularly important because it tends to place an upper limit on the plasma interception velocity and effective I_{sp}. Smaller, high-specific yield pulses combined with more ablation resistant materials could reduce minimum standoff distance requirements and increase I_{sp} considerably. For example, increasing the maximum stagnation pressure to 1000–2000 MPa (150,000–200,000 psi) from the 690-MPa limit assumed on Orion would increase I_{sp} by 20–40%.

Another notable advance is in the area of carbon nanotubes. These structures may not only serve as a superior plate material, but they may also provide a means for incorporating near-reversible energy absorption and release into the plate itself. Certainly, using advanced materials in the conventional shock absorbers of Orion and updating the design with modern computer modeling and controls would furnish better efficiencies.

Eliminating or greatly reducing pusher plate size through use of electromagnetic fields may provide another way of improving the transfer of blast energy to the vehicle. Application of recent electromagnetic and superconductor technologies could replace the pusher plate design completely, as in the MagOrion concept,[25] or provide a protective shield to minimize pusher plate erosion. The magnetic field would have an inherent shock absorber effect and would offset the increase in maximum pressure loads from relatively close detonations. In the limit, a very strong field surrounding a low-yield detonation could eliminate not only the pusher plate, but also the mass penalty associated with pulse shaping.

Environmental Issues

The most vexing issue facing NPP is its perceived impact on the environment. Earlier concepts assumed ground launch and later considered suborbital boost as the third stage of a Saturn V. It was later conceded that the concept had to be operated in space or in an orbit that presented no hazard to the Earth environment. Interestingly, Dyson[26] noted that the most extensive flight program envisaged by Taylor and himself would have added no more than 1% to the atmospheric contamination being created by open-air nuclear weapons tests circa 1960.

Undoubtedly, the same restrictions on NPP would hold today, and would also extend to noninterference with satellites and other assets in Earth orbit. But to what extent a fission-based NPP system could impact or harm the environment is not entirely obvious. For operations in interplanetary space, well beyond Earth orbit, there may be no effect, since the average exhaust velocity of the propellant and fission products is nearly an order-of-magnitude greater than solar escape velocity. Particles at that speed can traverse the entire solar system within a year. Even the most liberal use of such a system in the expansiveness of deep space would produce radiation many orders of magnitude less than that of the natural background arising from solar wind and cosmic rays.

The need for testing on or near the Earth may be obviated by the extensive data available from past nuclear tests, sophisticated computer models, and numerous methodologies for simulating radiation and debris effects. Final testing could possibly be performed using a prototype vehicle deployed in deep space. In effect, final demonstration of the technology would be conducted in an actual flight application. This is not unreasonable to consider, since other advanced propulsion technologies, such as solar and plasma sails, would require demonstration in space to fully validate their operation.

Recognizing that any future application of NPP must abide by the strictest safety and environmental standards, it is important to note that crew safety would be a primary goal in using this technology. The dramatic reductions in trip time afforded by its unique combination of high-Isp and high-acceleration would decrease exposure to space radiation and minimize the adverse effects of extended isolation. The feature of having a substantial pusher plate and propulsion assembly would provide excellent shielding for the crew, while the radiation shelters necessary to protect against solar flares would serve as extra protection during periods of applied thrust.

Risk Management

The most controversial aspect of the original Orion project was the risk it posed to the general population and Earth's environment. Launch and operation in low Earth orbit presented the greatest risk mainly from the potential for dispersal of radioactive products within Earth's atmosphere and magnetic field. Any application that could lead to such conditions would be strictly forbidden today.

Apart from this obvious point, the riskiest aspect of Orion was its use of individual, self-contained nuclear devices. (Ironically, this was one of its main strengths from a performance standpoint). The risk does not stem from the variability and malfunctioning of individual pulse units. Differences in yields, directionalization, detonation location and timing are averaged out over many pulses, and have little impact on overall mission performance. Rather, it arises from their physical and mechanical autonomy, which justifiably raise issues related to testing, nuclear proliferation, and national security.

In reality, the pulse units would be very difficult to set off and would be designed with multiple, failsafe arming features to prevent premature nuclear detonation in any accident scenario. Both electronic and hardware keys could be based on the exact implosion characteristics of each device. Disassembly or unintentional detonation of the chemical explosives would yield nothing more than chemical energy, debris, and small chunks of uranium. There are also many safeguards that would ensure reliability, safety, and security, so that any inappropriate attempt to set off or disassemble a device would result in its destruction. Finally, using these devices shortly after assembly would reduce the opportunities for theft or sabotage. This is in contrast to military stockpiles, which are stored and maintained for long periods of time, and are hence more vulnerable.

Still, it would be far better to avoid autonomy altogether by removing a critical initiating process from the pulse unit and incorporating it as a function of the spacecraft. Use of a system onboard the spacecraft to establish physical conditions needed at the start of the implosion process would greatly mitigate the potential for proliferation and misuse. Several of these approaches have been discussed and include lasers, electron beams, antimatter injection, electromagnetic compression, and high velocity projectiles. Such systems would add mass and complexity to the spacecraft design and would require great precision in their operation. However, the advantage is clear—it removes the issue of using autonomous nuclear explosives in space.

Conclusions

Even with the risk reductions and performance improvements described here, any future development of NPP would be highly controversial. There is no doubt that future acceptance of such an idea would demand convincing technological need and international involvement. As of now, there are several propulsion concepts that could be used for human missions to Mars. However, with conservative projections of technological readiness, these missions would be constrained to a 2–3 year duration with significant health risks to the crew.

If the need arose to conduct a Mars mission within a year or less, or if there were a desire to transport human or large payloads as rapidly as possible to destinations in the outer solar system, then the use of NPP becomes quite compelling. If such missions involved extensive international cooperation and the same technology were applicable to other common goals, such as Earth asteroid/comet defense, then there may be more acceptance for this type of technology in the future.

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