

Nuclear Space Propulsion: Overcoming the Chemical Barrier

Humanity has stumbled across an interstellar road block. Our current spacecraft technology lacks the power infrastructure and engineering designs needed to undergo longer voyages within reasonable time frames. However, an overhaul of space propulsion systems could enable humanity to increase the velocity and range of its spacecraft dramatically. Current space propulsion systems rely on bell-chambered chemical propulsion, and it would still take almost as much time to send a person to the moon as it did in 1969 with the touchdown of Neal Armstrong on its surface. In 2004, two 384-pound unmanned rovers took seven months to reach Mars as part of the Mars Exploration Rover Program (NASA, 2009). In order to improve the efficiency of these spacecraft, humans have begun to turn to newer sources of power. The development of nuclear power within the last century has allowed people to begin incorporating innovative propulsion designs. Nuclear power is currently a leading form of energy, and by applying it in conjunction with the laws of physics, humanity might be able to expand its boundaries in space. The following report covers the three major types of nuclear propulsion systems that have been investigated, along with their potential advantages, engineering problems, and political dilemmas.

All spacecraft propulsion systems rely primarily on Newton's Third Law of Motion. The third law states that any object that is subjected to a force will apply a force of equal magnitude and opposite direction to the initial force. The force and efficiency of a propulsion system can then be quantified by the terms thrust and specific impulse respectively. Thrust is simply a measure of the force exerted on the spacecraft which allows it to fly. Specific impulse is defined as the ratio of the pounds of thrust produced per pound of propellant consumed per second

(NASA, 2008). This means that the specific impulse is the amount of force generated given a set amount of propellant. The efficiency of two engines can be compared by determining which engine has the greater specific impulse value. The engine with the higher value can generate more power with the same amount of fuel. The more efficient engine will be able to fly longer and faster on the set amount of fuel.

Historically, propulsion systems have been almost exclusively designed as chemical engines. In order to generate thrust, these rockets rely on pumping unstable chemicals, namely liquid nitrogen and liquid hydrogen, into a reaction chamber. The chemicals then react violently, resulting in a rapidly expanding nitrogen gas that applies force to the reaction chamber within the rocket (Braeunig, 2009). The reaction chamber is specifically engineered into a bell shape in order to maximize the area on which force can be applied to the rocket. The downside to these chemical systems is that they must propel all of their own heavy fuel and are limited in speed by the rate of gas expansion, giving them low specific impulses. While chemical propulsion could provide the necessary power to journey into space, nuclear propulsion could dramatically increase the speed and distance of these expeditions.

There are three main kinds of nuclear propulsion systems that have been theorized or tested up to the present. Each of these designs comes with its own set of advantages, challenges, and problems. The designs include nuclear pulse propulsion, thermal nuclear propulsion, and nuclear electric propulsion. Pulse propulsion involves the detonation of fission bombs behind a spacecraft to generate thrust. Thermal nuclear and electric nuclear both utilize fission reactor technology to generate energy. In thermal nuclear systems, the heat energy created by the reactor takes the place of the liquid hydrogen in chemical rockets. Nuclear electric designs use a fission reactor to generate electricity which is then expelled out the back of the spacecraft as ions in

order to create propulsion. While all the designs share the characteristic of overcoming the chemical barrier, nuclear pulse propulsion is the most promising because of the major advances it brings in specific impulse and thrust capability.

Nuclear pulse propulsion involves creating a spacecraft which has a large, dense metal pusher plate at its base. The craft would be propelled by deploying atomic bombs and detonating them 100 to 1000 feet behind the vehicle; the resultant explosion would generate the thrust for the spacecraft (Shipps et al., 1964, p. 14). The immense amount of energy that can be released with the detonation of a nuclear device is what makes the design so potent. The pulse system is not restricted by temperature or power like its chemical counterparts. It overcomes power restrictions by detonating the bombs outside the craft, thus negating the need for cooling solutions and radiators. Nuclear pulse propulsion also escapes the temperature barrier because the pusher plate is exposed to extreme temperatures for only fractions of a second, which eliminates the chance of vaporization (Dyson, 1965, p. 141). The use of a nuclear pulse system also allows for a massive increase in thrust. The original researchers concluded that it was possible to create a functional shuttle weighing in at 10,000 tons (Shipps et al., 1964, p. 14). This is more than four times the current 2,200-ton standard used today (NASA, 2006).

Nuclear pulse propulsion could provide an enormous advance in space flight technology, but the creation of the system was hampered by politics. The investigation into nuclear pulse propulsion began as Project Orion in 1958 by a group of engineers and scientists composed of those who had created the atomic bomb and employees of General Dynamics Co. They spent millions of dollars on research in the next seven years and concluded that a nuclear pulse propulsion system was not only feasible, but completely possible (Dyson, 1965, p. 141). However, the project was ultimately shelved because of politics. Freeman Dyson, a renowned

physicist, wrote a paper entitled “Death of a Project” in which he explains that Orion was destroyed by four groups: the promoters of the test-ban treaty, the heads of the Department of Defense, the heads of NASA, and the scientific community. The test-ban treaty was the most notable because, as stated by astronomer David Darling (n.d.), “with the signing of the nuclear test-ban treaty by the United States, Britain, and the Soviet Union in August 1963, Orion, as a military-funded program calling for the explosion of nuclear devices, became illegal under international law.” At this point, funding ceased and the project dwindled until NASA officially discontinued it in 1965.

While nuclear pulse propulsion never made it to the assembly line, nuclear electric propulsion has already begun testing. Ground tests of a nuclear electric propulsion (NEP) engine are in progress at NASA’s Marshall Space Flight Center in Alabama. The initiative to develop a NEP system began in 2003 under the project name Prometheus (NASA, 2005). However, research on the subject dates back to 1906 when Robert Goddard established that particles could be accelerated to high velocities by using a magnetic field. This concept was incorporated into spaceflight with the creation of the ion thruster in 1964 (Darling, n.d.). The first primary ion propulsion system was finally created in 1998 with the launch of the Deep Space 1 probe (NASA, 2008). An ion thruster uses electricity to ionize a fuel (xenon and mercury have been used) and then accelerates the ions through an electromagnetic field in order to generate thrust. These early electric systems rely on solar power in order to generate the electricity and are consequently limited in the amount of power they can generate. NEP systems involve the use of an onboard fission reactor that can be used to create substantially greater amounts of electricity. NEP systems provide a large specific impulse and are the only type of nuclear propulsion currently under development. The downside to NEP systems is that they produce such a small

amount of thrust that the spacecraft design must be as lightweight as possible. The low thrust output also translates to slow acceleration and longer mission times, making it feasible primarily for long-term unmanned missions.

The drawbacks of NEP systems, however, make it necessary to investigate another potential design solution. Nuclear thermal propulsion (NTP) has the ability to produce immense amounts of thrust and a high specific impulse, but is not being actively pursued. The investigation into NTP technology began in 1955 at the Los Alamos National Laboratory, the same location where the atomic bomb was developed a decade earlier. The project evolved into NERVA (Nuclear Engine for Rocket Vehicle Application) in 1963 as Project Orion was coming to an end. The program oversaw approximately 23 reactor tests up until 1973 when the project was officially terminated (Darling, n.d.). NERVA's demise was a combination of funding cuts and lack of public interest in space flight. Presently, NTP is being reconsidered by NASA propulsion experts, but the chief obstacle is the theorized 1.5-billion-dollar cost of creating a NTP system (Reichhardt, 2001). The NTP system could be developed in three forms: solid core, liquid core, and gas core. Solid core, the form that made it into testing, expands upon the chemical design by replacing the nitrogen reactant with heat energy. This heat energy is generated by an onboard fission reactor and then used to super heat the propellant and force it out of the nozzle for thrust. Higher temperatures can produce more thrust, but the system is limited by the melting temperatures of the shuttle materials, roughly 3500 Kelvin [K] (DiPiazza & Mulas, 2006, p. 2). In the NERVA program, graphite was used as the reactor fuel because it limited the reactor temperature to 2500[K] (Irvine, 2001). Carbide was also theorized to be a usable fuel which would push the effective reactor temperature up to 3250[K]. Liquid core thermal systems use the same configuration as solid core but involve mixing the reactor fuel into

the propellant mixture, which allows the reaction to take place within the liquid mixture. This design provides a more efficient cooling solution and allows the reactor temperature to exceed solid core designs. However, liquid core designs remain purely hypothetical because the reaction of the nuclear fuel occurs much faster than the heating of the propellant. The gas core design involves the heating of the fuel into a plasma state which allows it to exceed the maximum structural temperature of the engine because it will not make contact with its surface (Frisbee, 2004, p. 1134). The engineering challenge that arises from gas core systems is controlling the fuel loss, and while solutions have been theorized, the system has never been created. Nuclear thermal systems stand on a middle ground in terms of power and feasibility between NEP and pulse propulsion, but politics and public disinterest have prevented the project from resurfacing at the present.

Ultimately, nuclear propulsion systems exceed the capabilities of chemical systems in several ways. In all forms, nuclear propulsion surpasses chemical engines in specific impulse by a large margin. Most forms of nuclear propulsion also bring large increases in the amount of thrust they can provide. Politics, ethical issues, and public disinterest have kept all but one of the nuclear systems from being developed, and although it is the least promising in terms of raw power, it can make a significant contribution to deep space exploration. If the general populace were once again to become interested in space exploration, rationalize the costs, and overcome the political barriers, nuclear pulse and thermal propulsion projects could potentially be reopened. Then, by harnessing the power of nuclear energy, humanity's next landing may not be on Mars, but one of Saturn's moons.

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