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ABSTRACT

The operation of nuclear rockets with respect both to rocket theory and to various fuels is described. The development of nuclear reactors for use in nuclear rocket systems is provided, with the Kiwi and NERVA programs highlighted. The theory of fuel element and reactor construction and operation is explained with particular reference to rocket applications. Testing sites and programs are illustrated. Future developments and applications are discussed. The conclusion that the NERVA engine is the only practical advanced propulsion system that can meet the requirements of the space transportation system in the 1980's and beyond is stated. A glossary, reading list, and motion picture list of related topics are included. (TS)

Nuclear Propulsion for Space

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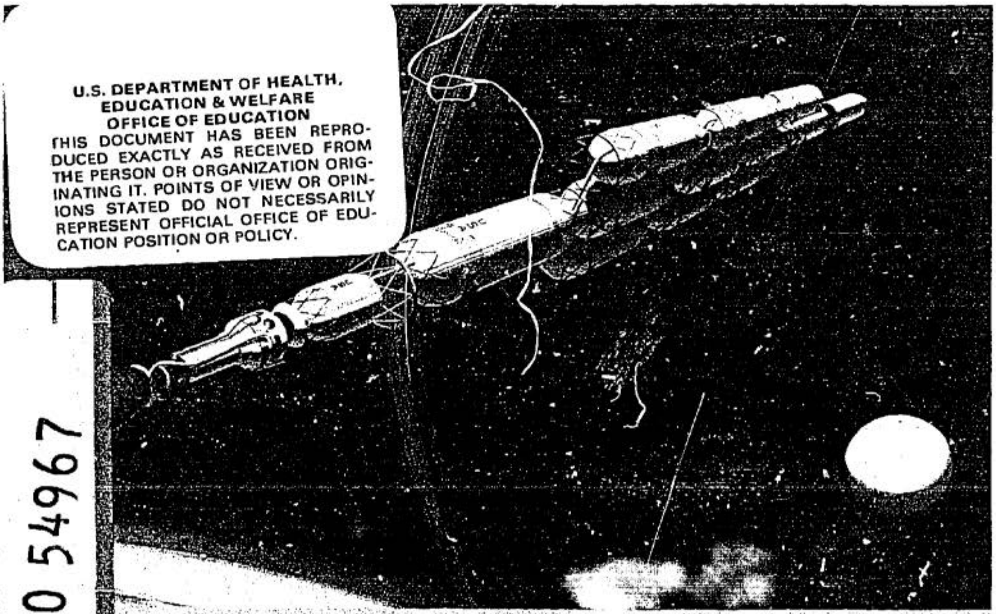
by *William R. Corliss and Francis C. Schwenk*



An Understanding the Atom Series Booklet

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The Understanding the Atom Series

Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

Edward J. Brunenkant

Edward J. Brunenkant, Director
Division of Technical Information

THE COVER

The cover shows a reusable nuclear stage, powered by the NERVA engine, leaving an earth orbit on a round-trip mission to the moon. The NERVA engine "fires" at least four times on this mission: To leave earth orbit, to go into orbit around the moon, to leave the moon, and to return to orbit around earth. This stage was delivered to orbit, where it was assembled, and refueled by multiple flights of the two stage space shuttle. To provide sufficient payload to support a lunar station, the nuclear stage carries 150 tons of liquid hydrogen in eight tanks. After the stage returns to earth orbit, it will be refueled, repaired, if needed, and checked-out for additional missions to the moon, to synchronous orbit, or to interplanetary space.

Nuclear Propulsion for Space

by William R. Corliss and Francis C. Schwenk

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United States Atomic Energy Commission
Division of Technical Information

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Nuclear Propulsion for Space

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ENERGY FOR SPACE TRAVEL

The secret of space travel is energy—immense amounts of energy. The first stage of the Saturn-V moon rocket generates as much energy each second as a million automobile engines. The energy leverage of nuclear fission eventually will give us spaceships that can sweep across the solar system and carry men to the farthest planets.

But the uranium nucleus is not broken to man's bidding easily. Our quest is for a means of uniting the almost limitless energy of the atomic nucleus and the rocket's unique ability to thrust through the vacuum of space. This difficult wedding of nuclear fission (age, 30 years) to the rocket (age, 1000 years) is the subject of this booklet.

In the words of Dr. Glenn T. Seaborg, Chairman of the U. S. Atomic Energy Commission: "What we are attempting to make is a flyable compact reactor, not much bigger than an office desk, that will produce the power of Hoover Dam from a cold start in a matter of minutes."

HOW A NUCLEAR ROCKET WORKS

The rocket concept was grasped by the first caveman when he pushed off from a lakeshore on a raft; *every action has an equal and opposite reaction* according to Newton's Third Law of Motion.* The caveman's action was pushing the shore away with his foot; the reaction was the surge of the raft onto the lake.

Actually, it is not necessary to have something solid to push against. The caveman could have propelled himself out on the lake by hurling rocks shoreward; as each rock left his hand, he and the raft would have moved a bit farther. It is the same way in airless space; propulsion in a given direction means throwing something away in the opposite direction. Instead of rocks, the ordinary chemical rocket expels a roaring jet of hot combustion gases. But the effect is the same. To make a nuclear rocket, the uranium nucleus must be fissioned† in such a way that something is expelled from the spaceship. We'll explain how later in this booklet.

Chemical rocket engines, jet engines, automobile engines—in fact, most of mankind's engines—extract heat from a fuel and turn it into motion through the expansion of hot gases. The nuclear rocket sprouts from the same family tree; it also creates hot high-pressure gas and turns it into thrust. The nuclear rocket is a direct descendent of the aeolipile, a steam-spouting "reaction engine" reputedly built a century or two before Christ by the famous Alexandrian engineer, Hero.

It is relatively easy to see how a hot gas expands against a piston in an internal combustion engine to do useful work. The piston presents the gas with something solid to push against. And the rocket engine operates in much the same way, except that the piston is replaced by the rocket nozzle. The hot gases created by chemical combustion or nuclear heaters issue from the throat of the rocket nozzle

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*Sir Isaac Newton, the great British intellect who lived from 1642 to 1727, formalized the basic laws of motion as we know them today.

†For an explanation of nuclear fission, see *Our Atomic World*, another booklet in this series.

and expand against its flared sides, pushing the nozzle (and the whole rocket) upward. The pressure against the nozzle walls is the reaction to the expulsion or pushing away of the hot exhaust gases.

The first reaction engine. In Hero's aeolipile, steam squirting from the two pipes caused rotation.

Looking at it another way, each molecule in the exhaust is like a small bullet shot from a big gun (the rocket engine). Indeed, if we think of the rocket engine as a continuously firing shotgun with molecular ammunition we are pretty close to the truth.

If the masses of these molecular "bullets" and their "muzzle velocities" are known, the rocket thrust can be computed from the simple equation:

$$F = \dot{m}v$$

where F = thrust (measured in newtons*),
$\dot{m}$ = the mass flow rate of the bullets or propellant, (in kilograms per second), and
v = the average muzzle velocity or exhaust velocity along the rocket axis (in meters per second).

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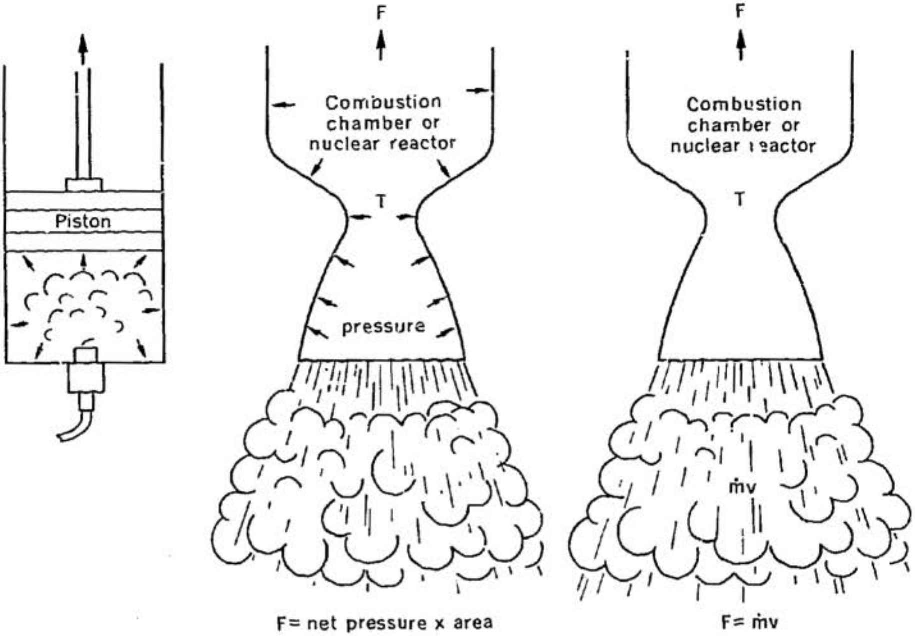
*Named for Sir Isaac and equal to the force necessary to accelerate 1 kilogram of mass 1 meter per second per second; a force of one newton = .225 lbs. Newton also introduced the idea of placing a dot over a symbol to indicate rate of change. For example, if v = velocity, $\dot{v}$ = acceleration.

Dividing F by $\dot{m}$ reveals that the thrust produced per unit mass flow of propellant is equal to v. In other words, the higher the bullet or propellant velocity, the more thrust



Hot gases expand against a piston, left, pushing it upward. Center, hot gases expand against a rocket nozzle, pushing it upward. The reaction thrust, F, can be computed either from the total net pressure against the nozzle and combustion chamber area, or from $\dot{m}v$ *(right). The two F's are identical.*

we get from each kilogram of gas that roars out the nozzle each second. We want to have a high exhaust velocity for good rocket performance because we can thereby accomplish a space mission with less propellant. We will show later that the nuclear rocket produces about twice the exhaust velocity of the best chemical rocket. High exhaust velocity is the greatest advantage of the nuclear rocket.

The question then is: How does a nuclear rocket generate high exhaust velocities? The key to the nuclear rocket's success lies in a simple equation from thermodynamics

$$v \propto \sqrt{T/M}$$

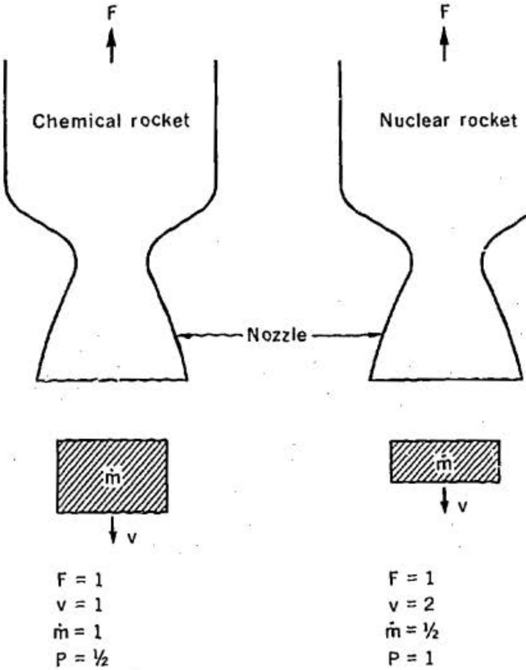
which says that the exhaust velocity, v, of any rocket is proportional to $\sqrt{T/M}$;

where T = the temperature of the hot gases just before they enter the nozzle throat, and

M = the average molecular weight of the exhaust gases.

It is obvious that for a high v value we wish to maximize the quantity $\sqrt{T/M}$.

Knowing that T and M control v, let us first try to manipulate T. Since T is under the square root sign, it will have to be quadrupled to double v, the exhaust velocity. Chemical



Nuclear rockets have twice the exhaust velocity of chemical rockets. Thus, for the same level of thrust, propellant mass flow is halved and power is doubled.

rockets already operate at temperatures close to 3000°K;* if the nuclear fuel is to stay in solid form, it is apparent it cannot go to 12,000°K, which is hotter than the sun's surface. In fact, today's nuclear rocket reactor fuels barely survive at 3000°K, the same general temperature level achieved in chemical rockets.

To avoid this impasse, something must be done to reduce M, the molecular weight, rather than to increase T. In a chemical (combustion) rocket, M does not drop much below 18, because the most convenient oxidizers have quite heavy atoms. For example, the advanced Centaur engine burns hydrogen with oxygen to form water (H_2O) for which $M = 18$. Chemical rocket exhaust velocities are thus limited mainly by the high molecular weights of the combustion products. As long as chemical fuels must be burned with oxygen or fluorine, chemical rocket exhaust velocities cannot be greatly improved.

In a nuclear rocket, however, combustion is not required: The nucleus fissions without chemical stimulation, and the propellant is not an engine fuel but a separate substance that is heated by the fissioning nuclei in a nuclear reactor. A nuclear rocket designer can heat up any propellant he wishes as long as it does not chemically attack his reactor fuel elements. Therein lies the secret of the nuclear rocket's high exhaust velocity—it can make use of a propellant with a low molecular weight.

In designing a nuclear rocket then, the first inclination would be to choose hydrogen gas as the propellant because hydrogen is the lightest of all molecules, with $M = 2$. Other possibilities—such as water ($H_2O : M = 18$), methane ($CH_4 : M = 16$), and ammonia ($NH_3 : M = 17$)—offered modest improvements over early kerosene-burning chemical rockets, but show no advantage over the newer chemical engines that burn hydrogen with oxygen. In the early days of nuclear rocketry, though, ammonia and methane were competitors of hydrogen because hydrogen was feared as a fickle, explosion-prone material that had to be stored as a liquid at a temperature of only 20°K (−253°C). In addition, it

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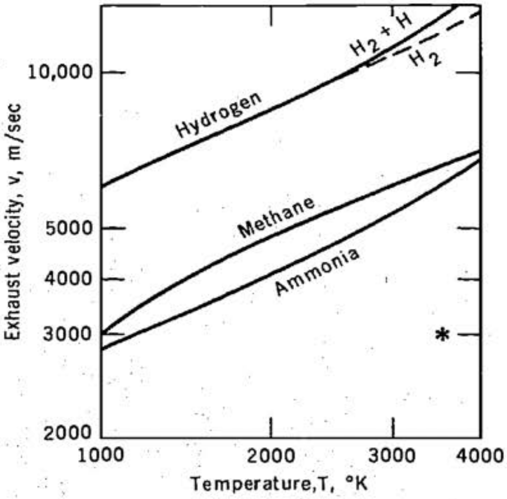
*Or 2727° centigrade; degrees Kelvin are measured above absolute zero and are equal in size to centigrade degrees. 0°C = 273°K.

was known that ammonia and methane dissociate* to a large extent at temperatures around 3000 °K, as their molecules collide violently with each other. Complete dissociation of methane into its five constituent atoms would bring M down from 16 to 3.2, and this would make methane much more attractive as a propellant. Nevertheless, hydrogen finally did win out over all competition, mainly because the dangerous handling problems were licked and because the nuclear rocket needed the even higher exhaust velocity promised by pure hydrogen if it was to achieve its full potential.



*Liquid hydrogen-liquid oxygen engine operating at 500 pounds per square inch pressure.

Plots of exhaust velocity. Methane and ammonia nuclear rockets do not appear to be much better than a hydrogen-oxygen chemical engine. A hydrogen nuclear rocket is superior to all.

Molecular hydrogen† also dissociates with heat; but, because the H—H chemical bond is so strong, dissociation

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*Or decompose into the constituent atoms making up their molecules.

†Hydrogen gas, H_2, is a molecule containing 2 hydrogen atoms.

is negligible at today's nuclear rocket temperatures. If atomic hydrogen could be used as a propellant, M would equal 1, and the exhaust velocity factor would multiply that of molecular hydrogen by $\sqrt{2}$. This is a development that will have to wait for future exploitation, however. The first operational nuclear rockets will spew hot molecular hydrogen out of their nozzles. With $M = 2$ instead of 18, as in hydrogen–oxygen chemical engines, the nuclear rocket exhaust velocity still will be more than double that of the best chemical rocket for the same temperature.

Doubling the nuclear rocket's exhaust velocity has one further consequence: It requires the nuclear heat source to generate more power. A simple equation for the power, P, in the exhaust gases comes from the kinetic energy (KE) equation:

$$KE = \frac{mv^2}{2}$$

but, since power is the *rate* of energy production, m is replaced by $\dot{m}$ and KE by P. Thus,

$$P = \frac{\dot{m}v^2}{2}$$

Using this equation, and $F = \dot{m}v$, we can see that if thrust is held fixed and exhaust velocity is doubled, propellant flow will be halved (as desired), but the power required to do this will be doubled. The price of increasing the exhaust velocity is increased power. From this relationship arises another important advantage of the nuclear rocket: The great reservoir of energy contained in its nuclear fuel can be turned into high exhaust velocity.

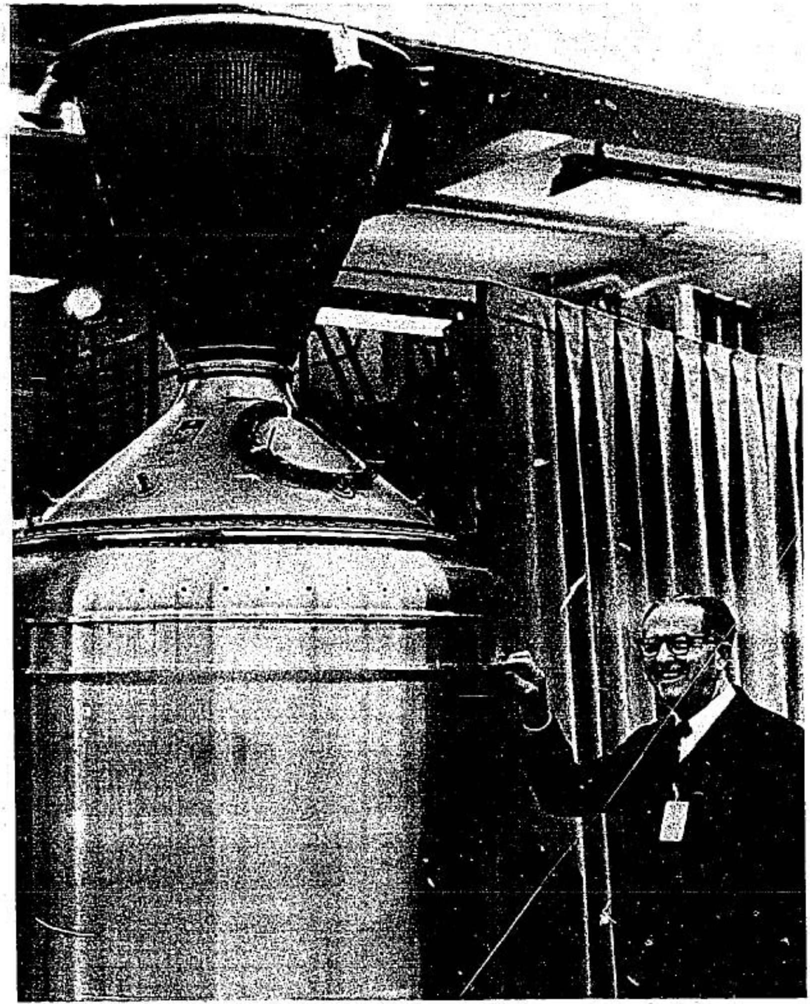
If we keep in mind three basic facts about nuclear rockets:

1. They convert fission-generated heat into the kinetic energy of rocket propellant,

2. Chemical combustion is not needed, and they can use low molecular weight propellants to attain high exhaust velocities,

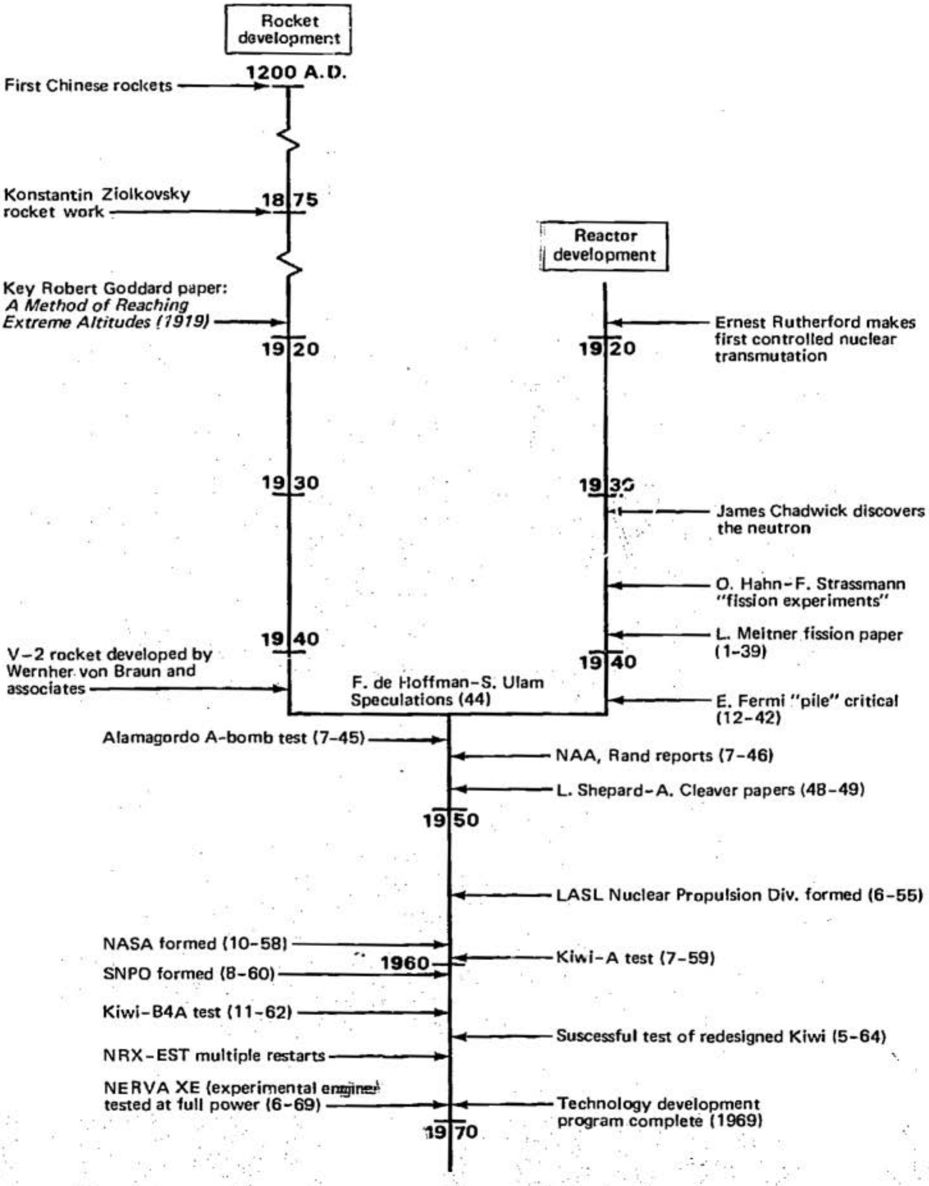
3. Their reactor fuel has a great deal of energy packed in it,

we can understand better the thoughts of the pioneers in nuclear rocketry as they tried to channel the power of the atom into high-temperature, lightweight reaction engines that would carry men toward the planets.



U. S. Senator Clinton P. Anderson of New Mexico, Chairman of the Senate Aeronautical and Space Sciences Committee, and a member of the Joint (Congressional) Committee on Atomic Energy, examines a Kiwi reactor during a visit to Los Alamos Scientific Laboratory.

Chronology of Rocket and Reactor Technology



FROM THE FIRST SPECULATIONS TO NERVA

"The Italian navigator has landed in the new world." This was the text of the cryptic message sent by Arthur Compton to other American scientists working on nuclear research when Enrico Fermi* attained the first self-sustaining nuclear chain reaction. The precise moment had come at 3:20 p.m. on December 2, 1942, in a squash court at the University of Chicago, as neutron-absorbing cadmium rods were pulled slowly from Fermi's "pile" of graphite and uranium. In the context of this booklet, Compton's telephone call was even more prophetic than he intended, because Fermi had not only discovered the new world of the atom but had also given man an energy source with which he will be able to explore worlds far beyond the earth.

Fermi's success set scientists and engineers to wondering about what constructive things could be done with the results of nuclear research. In 1944, Stanislaus Ulam and Frederick de Hoffman, at a New Mexico center that later became the Los Alamos Scientific Laboratory (LASL), mused that the power of the atomic explosive might somehow be controlled to launch space vehicles. Ulam and de Hoffman were following the thoughts of the great master of science fiction, Jules Verne, who, in an amazing 1865 novel, *De la Terre a la Lune* (From the Earth to the Moon), wrote that the Baltimore Gun Club fired a manned projectile to the moon from a huge cannon emplaced near Cape Canaveral, now Cape Kennedy, Florida. The use of nuclear explosions for propulsion never proved feasible, but Ulam and de Hoffman started people thinking about a less violent source of nuclear energy—the nuclear reactor—in which heat is released slowly and controllably.

But ideas rarely come to fruition unless a practical need beckons. There was no such thing as a "space program" in 1945. But near the close of World War II, German V-2 rockets had proved they could carry 1600 pounds of amatol explosive 200 miles from Nazi-held territory in

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*Fermi, an Italian-born Nobel Prize winner, came to the United States in 1938 and headed the research team that built the first nuclear reactor. See *The First Reactor*, a companion booklet in this series.

Europe to London. What if the V-2s had carried atomic bombs? The thought was unsettling. Soon designs for Intercontinental Ballistic Missiles (ICBMs) began to take shape on drawing boards around this country. Some of these big rocket designs were nuclear at both ends —they had nuclear warheads and nuclear engines. Secret reports issued in July 1946 by North American Aviation, Inc., and Douglas Aircraft Company (Project Rand) are landmarks in the history of nuclear rockets. The reports underlined the great promise of the "heat transfer" nuclear rocket, noting its high exhaust velocity, its attainment of very high temperatures, and its high rate of heat transfer. The reports also noted that there were problems to be solved.

The military rocket work naturally was classified as secret by the Air Force. However, at the Applied Physics Laboratory of the Johns Hopkins University in Maryland (near Washington, D. C.) a group of engineers, who were unaware of the ICBM work and did not have access to the secret reports, innocently proceeded to duplicate all the important findings of North American and Douglas. Their unclassified report was published in January 1947. It was obvious that any engineer with a slide rule and a few pieces of paper could discover the essentials of the nuclear rocket without much help.

In 1948 and 1949, two British space buffs, A. V. Cleaver and L. R. Shepherd, again duplicated most of the secret nuclear rocket fundamentals in a classic series of papers published in the *Journal of the British Interplanetary Society*. Not long before the English report appeared, the American-educated Chinese scientist, H. S. Tsien, had reported his studies on the application of nuclear energy to rockets and other "thermal jets" at a Massachusetts Institute of Technology seminar. The basic principles of the nuclear rocket could be concealed no longer. As a sidelight, it is interesting that Shepherd went on to become a key man in Britain's atomic energy program, and Tsien later returned to China where he was a principal figure in the development of the Peking government's atomic bomb.

Although the bonds of secrecy had been broken, interest in nuclear rockets declined precipitously in the late 1940s. The chief "undertaker" at the funeral was a careful, competent technical report by scientists at North American

Aviation concluding that the nuclear rocket did not seem applicable to ICBMs. Furthermore, the North American report mentioned the (then) fantastic temperature of 5700°F (3400°K) as necessary for the nuclear reactor. Few engineers could swallow the idea of building a reactor that would have to operate at temperatures twice the melting point of steel. So, the nuclear rocket languished, nourished only in a desultory and indirect way by the Atomic Energy Commission—Air Force nuclear aircraft program. Robert W. Bussard, one of the early champions of the nuclear rocket, put the situation well:

> "Nuclear rocketry had been effectively written off as a dead end by most of the missile and rocket people (who didn't really understand nuclear energy and liked chemical energy better anyway) and most of the reactor people (who thought the whole idea of nuclear flight of any sort was generally loony)."

It was Bussard, in fact, who did much to resurrect nuclear rocketry. Working in the nuclear aircraft development program at Oak Ridge National Laboratory (ORNL) in Tennessee in the early 1950s, he was able to show that the earlier nuclear rocket studies had been too negative and too conservative. He was convinced that nuclear rockets *could successfully compete* with chemical rockets on long flights with heavy payloads. Bussard's studies and personal salesmanship were decisive. The Air Force in early 1955 decided to reexamine nuclear rockets as ICBM thrusters.

The Air Force scientists and engineers recognized, along with everyone else, that the most critical problem of the nuclear rocket was that of developing a high-temperature-resistant material. What material would hang together at 3000°K? To help answer this question, Los Alamos Scientific Laboratory formed the Nuclear Propulsion Division under Raemer E. Schreiber. Concurrently, a similar group was created at the Lawrence Radiation Laboratory in California.* In mid-1956, budget cutbacks forced consolidation at Los Alamos of all the nuclear rocket work, while Livermore took on the task of building a nuclear ramjet engine. In an unintentional canine paral-

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*Both the Los Alamos and Livermore laboratories are operated for the AEC by the University of California.

lelism, the rocket program was dubbed Project Rover and the ramjet was labelled Project Pluto.

Curious code names have always been part of nuclear and space lore. As part of Rover, there was Dumbo, a "pachydermal" reactor concept, and a huge nuclear-powered "bird" named Condor. Then came the Kiwis. A kiwi, as every New Zealander knows, is a tailless, hairy-feathered bird that the native Maori people named for its shrill call. The kiwi cannot fly, and its nuclear namesake could not either. The first Kiwis (Kiwi-A's) comprised a series of heavy, "battleship" test reactors that were fired *nozzle up*, as if to emphasize their inability to leave the earth.*

The Kiwis were an essential prelude to practical nuclear rockets. Materials tests in Los Alamos laboratories had shown that graphite (like the material in pencil leads) was a likely structural material to withstand 3000°K. Indeed, graphite's strength *increases* with temperature up to about 3300°K; at 3900°K, it sublimes† instead of melting. What better way was there to test this strange material than to disperse uranium carbide fuel in it and build a reactor? Kiwi-A was the result.

Kiwi-A was fired for 5 minutes by Los Alamos at Nevada Test Site in July 1959, using pressurized hydrogen gas as the "propellant". It generated 70 megawatts of heat power and reached temperatures as high as 1777°K. Kiwi-A was the first attempt to translate a decade of calculations and paper studies into hardware.

Two more Kiwi-A reactors were tested in 1959 and 1960 in order to (1) check reactor design, and (2) test the practicality of coating the graphite fuel elements with niobium carbide for protection against corrosion by the hot hydrogen propellant. In essence, the Kiwis were "pilot plants" that showed engineers how to build better engines.

The climate of official support for the nuclear rocket project changed markedly in the late 1950s. First, the Atlas (chemical) ICBM had by that time proved itself capable of carrying powerful nuclear warheads to just

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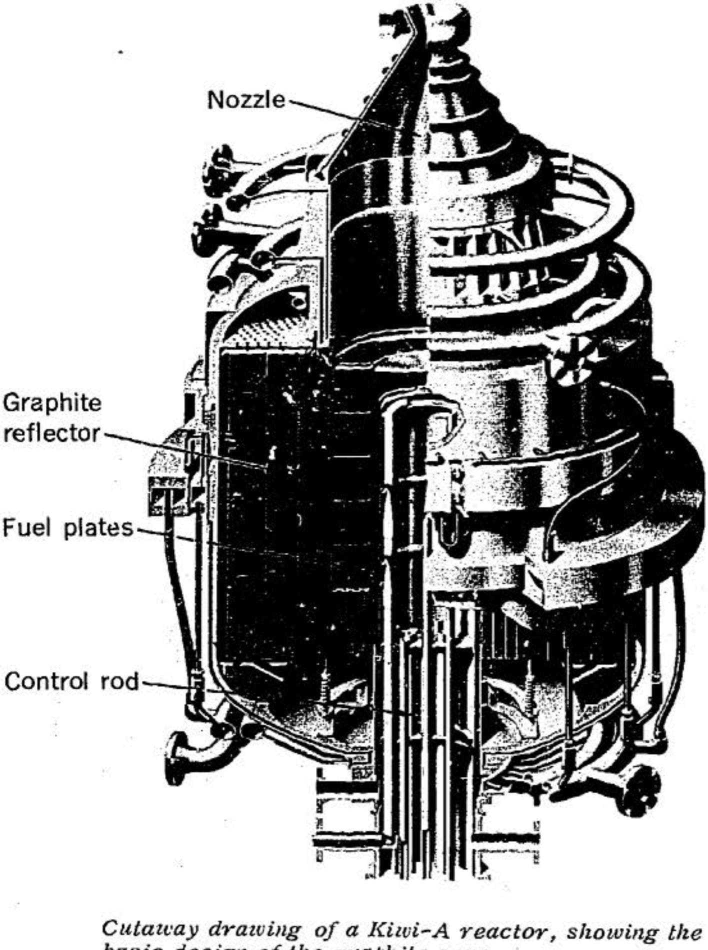
*They were not intended to fly, so a downward exhaust would only have caused problems; the interest at that time was only in the reactor operation. However, full-scale nuclear rocket engines have since been tested nozzle-down.

†Turning directly to vapor without going through a liquid phase.



Cutaway drawing of a Kiwi-A reactor, showing the basic design of the graphite core.

about any spot on earth. Therefore, the Air Force no longer needed nuclear-powered rockets to deliver weapons. Save for another event, the nuclear rocket engine might have died a second time then and there. But on October 3, 1957, the Russians signalled the beginning of the international space race by orbiting Sputnik I, the first man-made earth satellite. A month later they placed a live dog in orbit.

The National Aeronautics and Space Administration (NASA) was created in this country on October 1, 1958, by President Eisenhower's Executive Order 10783, to cope with this Russian technological threat. In the process, the AEC–Air Force partnership in nuclear rocketry was transformed into an AEC–NASA activity. In August 1960, the joint AEC–NASA Space Nuclear Propulsion Office (SNPO) was formed* to push toward an operational nuclear engine that would aid the U. S. in the race to the moon and planets.

Unperturbed by the administrative manipulations, nuclear rocket engineers were greatly encouraged by the Kiwi-A successes. Plans were laid for a series of more powerful test reactors, the Kiwi-B's, which would run on frigid liquid hydrogen† rather than gaseous hydrogen. The optimistic outlook also set SNPO workers to looking for industrial contractors to build a flyable nuclear engine. The NERVA (Nuclear Engine for Rocket Vehicle Application) Program began in the fall of 1960, when SNPO requested bids from interested companies. After a close competition, Aerojet-General Corporation was selected in July 1961 to build the engine (structure, pumps, etc.), and the Westinghouse Electric Corporation's Astronuclear Laboratory was chosen to construct the nuclear reactor, based on the Kiwi work of Los Alamos. In May 1962, the NASA Marshall Space Flight Center at Huntsville, Alabama, took another step by signing the RIFT (Reactor In-Flight Test) contract with the Lockheed Missiles and Space Company. Lockheed was to build a flight test vehicle for the Aerojet NERVA engine. This aggressive planning was commendable, but it proved to be premature because no operational missions were assigned to the RIFT system.

The new Kiwi-B reactors were designed to run at about 2300°K at 1100 megawatts, ten times the Kiwi-A power, sufficient to generate about 27.5 tons of thrust in space.

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*In 1970, the joint office was renamed the Space Nuclear Systems Office, when it was assigned the additional responsibility of providing nuclear-electric power for space missions.

†Hydrogen is liquid at temperatures less than 20°K. For a description of the extensive low-temperature technology that supports nuclear propulsion for space, see *Cryogenics, the Uncommon Cold*, another booklet in this series.

Kiwi-B4A was towed off to the R-MAD Building (see p. 41) where engineers picked it apart with remote manipulators. The reactor core showed widespread damage. Many opinions were ventured about the cause, but the most reasonable pointed to "dynamic" failure. That is, the high-pressure hydrogen gas had caused the graphite fuel elements to vibrate—that is, spaces in the reactor alternately became pressurized and depressurized. This caused the elements to vibrate and impact each other.

A good engineer views testing philosophically. After all, it was far better to have a failure out on the Nevada desert than on a spaceship halfway to Mars. The path ahead was clear. All of 1963 was devoted to confirming the diagnosis of vibration-induced failure. Reactor components were systematically tested in streams of hot high velocity hydrogen. "Cold-flow" tests with complete reactors, but generating no heat, were carried out. Gradually, a new vibration-resistant reactor was designed. In this sense, the Kiwi-B4A test was successful.

Hot testing of the new Kiwi nuclear reactors resumed in May 1964, only 18 months after Kiwi-B4A. Since then, a long series of highly successful tests has proved the redesigned nuclear core to be sound. Included in the series were the following:

May 1964	One power test, Kiwi-B4D
August–September 1964	Two power tests, Kiwi-B4E
September–October 1964	Two power tests, NRX-A2*
January 1965	Kiwi-TNT, a nuclear safety test
April–May 1965	Three power tests, NRX-A3
June 1965	One power test, Phoebus-1A
February–March 1966	Ten starts, Engine System Test, NRX–EST
June 1966	Two power tests, NRX-A5
February 1967	Two power tests, Phoebus-1B
December 1967	One power test, NRX-A6
June–July 1968	Three power tests of Phoebus-2A. Peak power reached: 4200 megawatts.
November–December 1968	Two power tests of Pewee-1, a fuel-element, test-bed reactor.
December 1968–August 1969	Total of 28 starts of the NERVA ground experimental engine (XE).

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*NRX stands for NERVA Reactor Experiment. See Glossary, page 54 for explanations of other code names.

The rocket reactor test program achieved a major milestone when the NRX-A6 reactor was operated at full-power for 60 minutes, a running-time sufficient for many space missions.

Of great significance were the Engine Systems Tests (ESTs). For the NRX–EST series, all major engine components were assembled—turbopump, hydrogen-cooled nozzle, control equipment, etc.—into a "breadboard"* engine. This close approximation to a real engine operating in space was started, shut down, and restarted in different ways. In short, the complete engine was put through its paces just as it would be on a real space mission. The real import of the NRX–EST series is that it showed that *a complete nuclear rocket system can start on its own power and operate stably over a wide range of conditions.*

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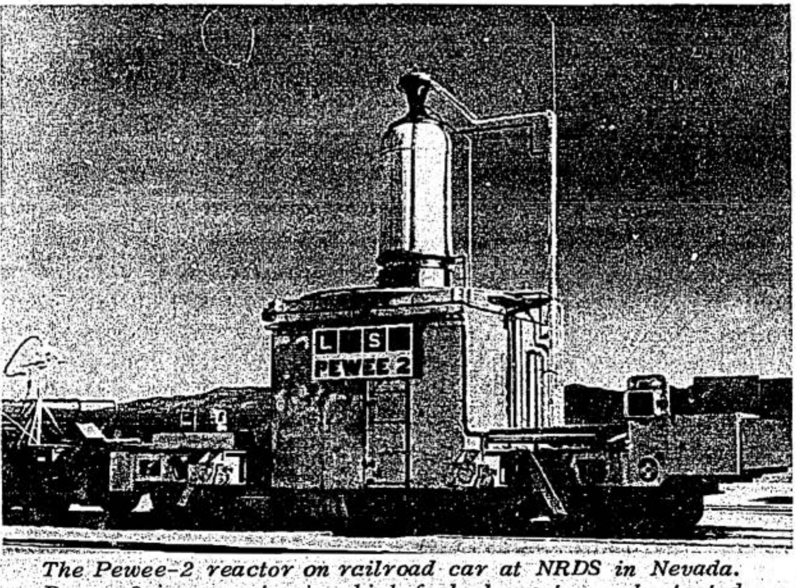
*A breadboard engine is one that includes all principal components of a flight-test system, but is arranged to be convenient for the test, and not as it would be in flight.



The Pewee-2 reactor on railroad car at NRDS in Nevada. Pewee-2 is a reactor in which fuel elements can be tested at conditions very close to (or even worse than) those encountered in an actual nuclear rocket engine.

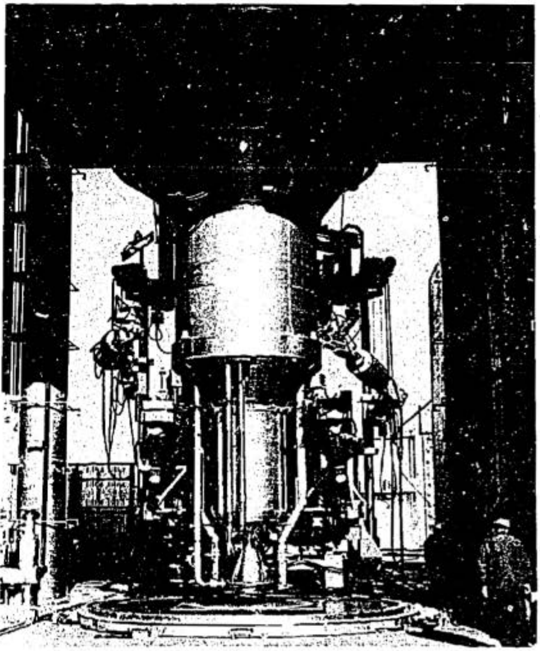
Further details of this EST test series are listed in the table on p. 22.

The test in June 1965 introduced the Phoebus nuclear rocket reactor series. The Phoebus reactors are best thought of as "tools" to advance nuclear rocket technology. For example, they incorporate significant advances over the Kiwis in terms of higher temperatures, higher power density in the core, and longer life—all factors that will lead to better nuclear rockets.

A most important series of engine tests commenced in December 1968, when the NERVA ground experimental engine, called the XE for short, was first put through its paces. The XE was similar to the NRX/EST but its components were arranged in a configuration closer to that which would be used in an actual flight system. For example, the liquid-hydrogen run tank was closely coupled and the test compartment was partially evacuated to simulate space conditions more closely. In fact, the XE tests were as much a test of the ETS-1 (Engine Test Stand 1) as of the engine itself. The XE series was concluded in late August 1969, logging a total of 28 power tests at various power levels. The total engine operating time was just under four hours. The XE was started successfully from a wide variety of starting conditions, demonstrating that a nuclear rocket can meet the requirements of a space transportation system.

In addition to developing better graphite reactors such as Phoebus, NASA-AEC experts have studied new types of nuclear rockets in which the fuel elements are made from tungsten, another material with good strength at very high temperatures. Even more adventurous are the studies of the so-called "gas-core" reactors in which the nuclear fuel itself is in gaseous form, retained within the rocket by centrifugal forces exerted as the fuel and propellant gases are spun about the rocket axis.

Although such advanced concepts undoubtedly will play a role in nuclear rockets of the distant future, we must focus our attention now on the graphite-core nuclear rocket. By the end of 1969, it was obvious that the graphite nuclear rocket had weathered all administrative and technical



The Xe installed in ETS-1 in Nevada. The XE has been the engine closest to actual flight configuration.

storms and reached the point where a flyable NERVA engine could be developed.

BUILDING AN ENGINE FOR SPACE

A nuclear rocket engine is considerably more than a heater of hydrogen. It is true that the engine is built around the reactor core—the wellspring of energy—but something else has to transport hydrogen propellant from tank to reactor; something else has to convert heat to thrust. The engine, in fact, has five major segments:

1. The nuclear reactor heat source.
2. The pump that pulls liquid hydrogen from its tanks and forces it through the reactor.
3. The nozzle, the prime mover that transforms heat to thrust.
4. The structure that physically holds all the pieces together.

Engine System Test (EST)—Summary of Power Tests

Start	Date	Maximum power (Mw)	Maximum temperature	Duration (min)	Partial list of experiments
1	Feb. 3, 1966	440	1420°K	11	"Bootstrap" start, temperature response studied.
2	Feb. 3, 1966	250	1140	13	Start with chilled reflector temperature limiter test.
3	Feb. 11, 1966	230	1110	9	Start with fixed control drums. Control-drum response tests
4	Feb. 11, 1966	160	806	-	Low-pressure start (aborted).
5	Feb. 11, 1966	350	1440	22	Bootstrap start. Pressure-response tests.
6	Mar. 3, 1966	1090	2280	6	Bootstrap start, run at normal design power and temperature.
7	Mar. 3, 1966	1040	2050	15	Bootstrap start. On-off controller test.
8	Mar. 16, 1966	170	833	-	Control positioning error led to automatic shutdown.
9	Mar. 16, 1966	1090	2270	18	Low-pressure start. System-response tests.
10	Mar. 25, 1966	1130	2320	16	Duration test at design power. System-response test at design power.
				110 minutes (including 28 minutes at full design power)	

5. The controls that force all engine components to march in step at the command of the spacecraft pilot.

Besides the system unity imposed by the structure and controls, the engine parts have to fit together thermodynamically. To breathe "life" into a nuclear rocket there must be a "starter", like that in an automobile, intrinsic in the system. The engine must "catch", become self-sustaining, and generate useful power. For this to happen, two energy sources must be found: One to start the engine and another to power the pump that keeps propellant flowing through the engine. A nuclear reactor heat source all by itself would be no more useful than an unharnessed gasoline flame would be in driving an automobile.

The Biggest, Hottest Reactors Ever Built

The heart of the nuclear rocket engine is, of course, the reactor. In the NERVA engine the reactor must generate upwards of 1500 megawatts of thermal power — more than the output of 15,000 Volkswagens or 50,000 home-heating furnaces — and still not weigh the rocket down. A temperature of 2500°K can be reached, according to reactor and full-scale engine tests in Nevada. Power levels of 4200 megawatts have already been attained. NERVA is as powerful and three times hotter than the reactors in any earthbound commercial nuclear-electric generating plant in the U. S. The NERVA engine, however, does not have to operate for years like its commercial counterparts; it can run at 2500°K only because a few hours of operation are sufficient for most space applications.*

A pile of uranium and graphite does not make a rocket reactor, although this was the way Enrico Fermi achieved the first self-sustaining chain reaction in 1942. Four requirements control reactor design: (1) The need to attain

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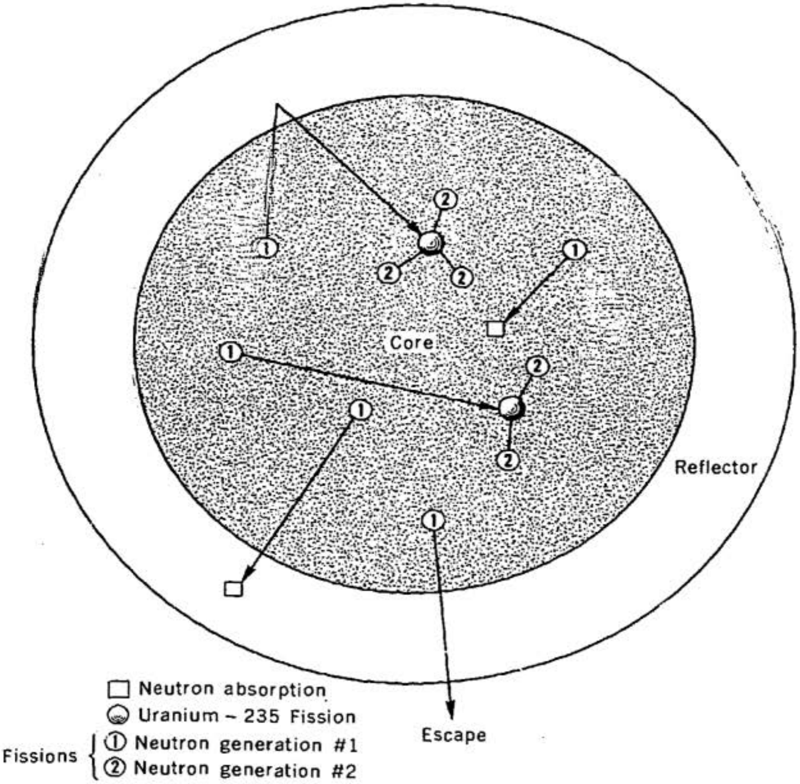
*Another AEC program develops space reactors that operate at *low* power levels for *long* periods of time. See *Nuclear Reactors for Space Power,* a companion booklet in this series.



Reactor criticality occurs when exactly one neutron from each fission reaction goes on to cause another fission reaction. Sketch shows five neutrons from Generation No. 1 producing two new fissions and five neutrons in Generation No. 2. Three neutrons in Generation No. 1 are lost through escape and absorption.

a critical mass;* (2) The need to remove *all* generated heat; (3) The need to raise and lower power at will, or control the reactor; and (4) The need to maintain structural integrity at high temperature and under the forces exerted by the high velocity hydrogen gas.

Attainment of a critical mass is a matter of "neutron economics", because it is the cloud of invisible neutrons

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*The smallest mass of fissionable material that will sustain a chain reaction. See *Nuclear Terms, A Glossary,* a companion booklet in this series, for definitions of unfamiliar terms.

coursing through the reactor that stimulates nuclear fission and thence power production. Each fissioned atom of uranium-235 produces $2\frac{1}{2}$ new neutrons on the average. If the rate at which fissions occur (and consequently the power level) is to remain constant, *exactly one* of these $2\frac{1}{2}$ neutrons has to go on and cause another fission. Reactor "criticality" occurs at just this point. This balance sheet leaves $1\frac{1}{2}$ neutrons per fission that can escape the reactor altogether or be absorbed in nonfission nuclear reactions.*

To prevent *too many* neutrons from escaping, a material is placed around the reactor to reflect some errant neutrons back into the core. Excessive neutron absorption can be avoided by using core and reflector materials that have

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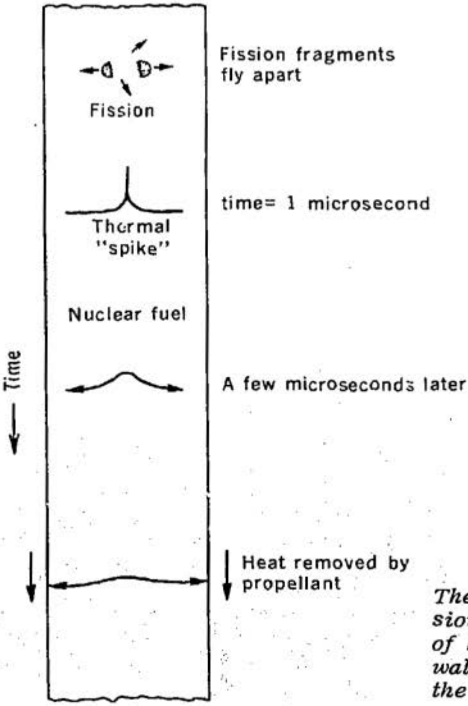
*See *Nuclear Reactors*, a companion booklet in this series, for an account of reactor construction.



The kinetic energies of the fission fragments appear as a pulse of heat that flows outward to the walls of the fuel, where it heats the rocket propellant.

little appetite for neutrons; fortunately, graphite has just such a "low neutron absorption cross section". Naturally, *enough* uranium-235 atoms must be dispersed throughout the graphite core so that the questing neutrons can find and fission them. But if there is too much uranium mixed with the graphite, fuel element structural strength is reduced. Core design requires a balancing of all these considerations, plus one more.

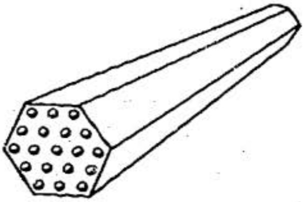
Almost all the energy released by uranium is first incorporated in the kinetic energy of two large fission fragments that fly off in opposite directions as a nucleus splits (Newton's Third Law again), peppering surrounding atoms. In a few millionths of a second, the kinetic energy of the heavy fragments is transferred to the nearby atoms, setting them to vibrating. A wave of heat spreads out from the fission site. If this heat is not removed, core temperatures will quickly rise beyond the sublimation point of the graphite fuel.

The reactor core, therefore, has to be designed in such a way that all this fission-generated heat is transferred to the hydrogen gas that is to be driven through the reactor by the pump. This means that the reactor must be perforated with holes that carry the hydrogen—serving here as a reactor coolant—through and past the hot fuel to the nozzle. If the coolant passages are too large, the size of the whole engine becomes so great it is unacceptable for space use. Holes that are too small cause high friction losses that impose powerful forces on the reactor structure. The designer must avoid these extremes and still provide enough coolant passage area to remove all the heat. (Note that the rate of heat transfer to the hydrogen is proportional to the area inside the holes and to the temperature difference between the hole wall and the center of the hydrogen stream.)

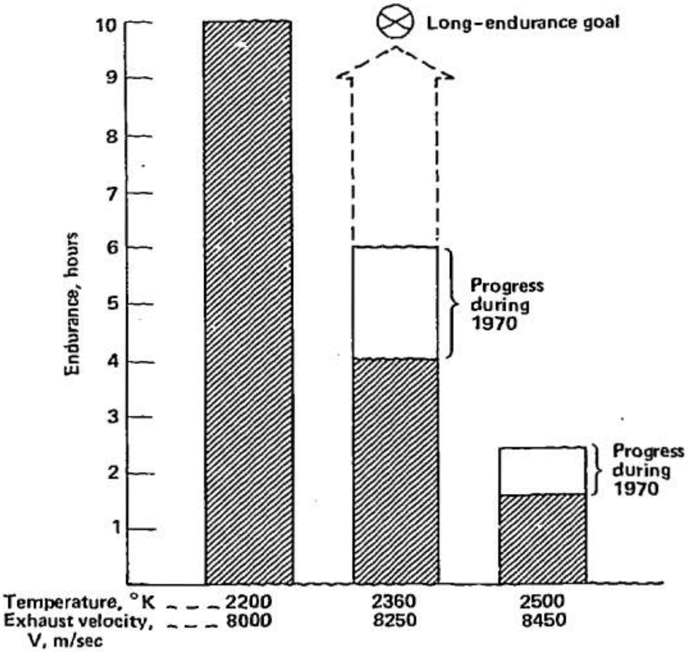
The basic fuel structure within the reactor core is called a fuel "element". The NERVA fuel element is a long hexagonal piece of graphite pierced by 19 holes that carry the hydrogen gas lengthwise through the reactor. The fuel elements are stacked together in a close array so that the hydrogen gas driven into the reactor by the pump encounters thousands of long, but very narrow, holes about one-tenth of an inch (0.25 cm) in diameter. It is in these holes that the gas picks up the heat generated in the body of the fuel element by the fissioning uranium.

Nuclear rocket fuel elements operate under extremely severe conditions: (1) temperatures that reach over 3000°K internally; (2) power densities of kilowatts per cubic centimeter; (3) intense levels of nuclear radiation; and (4) many thermal "cycles" (transients) that can crack the fuel elements just as boiling water cracks a heavy glass tumbler. On top of these problems, the hydrogen gas driven into the holes of the fuel element will react chemically and corrode the graphite structure unless protective coatings are added. Because the success of the nuclear rocket depends upon fuel elements that retain their integrities despite these infernal conditions, much of the AEC effort has gone into extending the life of graphite fuel elements at high temperatures.

Excessive hydrogen corrosion can be prevented by coating the fuel element holes with a metal carbide, such as niobium carbide. Ceramicists solve the other problems by trying different combinations of graphite powder, uranium carbide, and binder materials until they have a fuel element that can hold together under some of the worst conditions man can create. During the nuclear rocket program, there has been a progression of better and better fuel materials. The goal of the NERVA program has been a fuel element that will heat hydrogen to 2360°K and survive for 10 hours.



Sketch of a NERVA fuel element. The hexagon measures 0.75 inch (1.8 cm) across the flats (the sides of the element). Each hole is 0.1 inch (0.25 cm) in diameter.

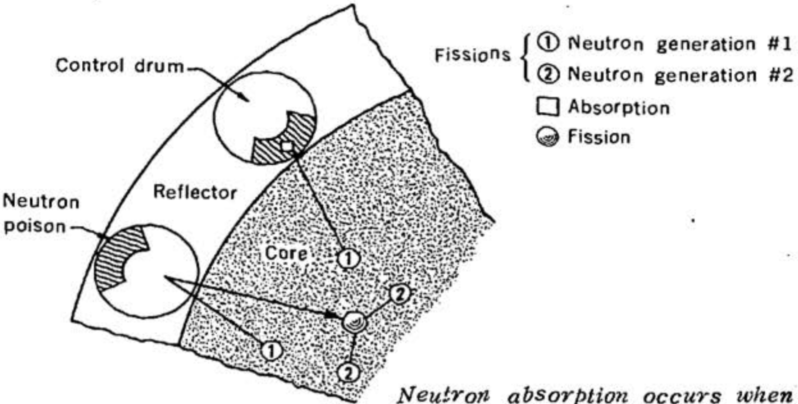


Lifetimes of NERVA fuel elements at different hydrogen temperatures.

Actually, there are two factors that control the size of the reactor core. Sometimes, the core has to be made bigger so that enough hydrogen can be forced through it to remove all the heat generated; it is then termed "heat-transfer limited". On the other hand, if the size of the core has to be increased just so enough fuel can be added to make it critical, it is called "criticality-limited".

To raise or lower the reactor power, the neutron economy must be upset, or altered. Control drums help perform this task in the NERVA reactor. The control drums are cylinders covered on one side with a neutron "poison" such as boron. When all the drums' absorbing faces are turned inward, neutrons that would otherwise be reflected back into the core to cause new fissions are absorbed by the poison instead. To start the reactor, motors slowly rotate the control drums, moving the poisons away from the core regions, thus giving the neutron economy a boost. If the drums are turned far enough so that each neutron in

Generation No. 1 causes 1.1 fissions in Generation No. 2, 1.21 in Generation No. 3, and so on in a continuing progression, the reactor power will rise very rapidly. Unless the control drums are returned to the exact point where criticality occurs, reactor power will rise toward infinity.



Neutron absorption occurs when the neutron "poison" sides of the control drums are turned toward the reactor core. In an actual control system all drums turn together.

Because neutron generations are only milliseconds apart, neutron "population explosions" (and reactor power changes, too) can come about very quickly.

An interesting feature of practical reactor control, however, is that almost identical control drum settings can produce stable power levels of 1 watt or, say, 10,000 megawatts. Reactors are "rate-controlled", that is, doubling the amount of displacement of the drum does not double the power level, but rather doubles the rate at which the power level changes.

The reactor core is supported by a support plate, tie rods, and side restraint components. This side or lateral support system has been developed to eliminate vibration and to accommodate the change in core dimensions arising from the thermal expansion of the core.

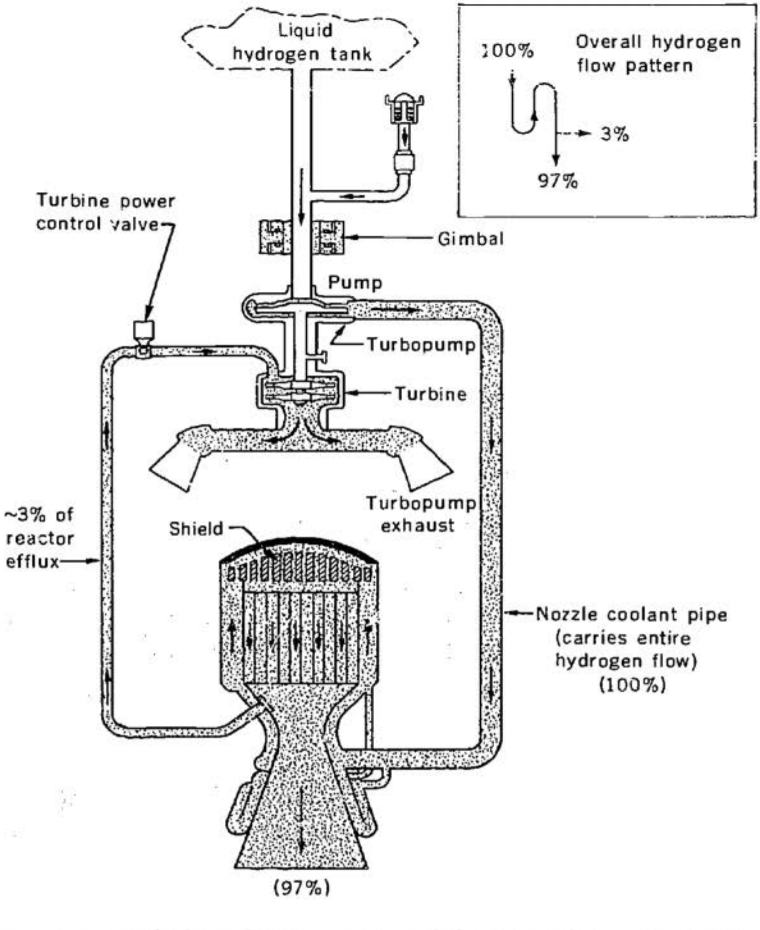
The Artificial Maelstrom

The NERVA pump must raise the pressure of liquid hydrogen by about 97 atmospheres (1300 lbs per square inch) while delivering nearly 3 tons of it a minute to the reactor. Not only is this a huge volume of fluid to handle (liquid hydrogen has only about one-tenth the density of water), but the process consumes a huge quantity of power. Two types of pumps can be considered: Centrifugal and axial-flow. In a centrifugal pump, liquid hydrogen at the intake (near the pump shaft) is caught by spinning blades (impellers) and flung outward toward the pump rim by centrifugal force, where it leaves through a diffuser at a higher pressure. An axial-flow pump is something like a series of fans mounted on the same shaft, driving the liquid hydrogen along parallel to the pump shaft.

The centrifugal pump employed during the Engine System Tests consumed about 5 million watts of shaft power. Where does all this power come from? In space, the only answer can be: From the reactor itself. Some of the energy imparted to the hydrogen by the reactor must drive the turbine that turns the pump. As we shall see a little later, this energy comes from the engine nozzle and the outer sections of the reactor in a mode of engine operation called the "full-flow" or "topping cycle".

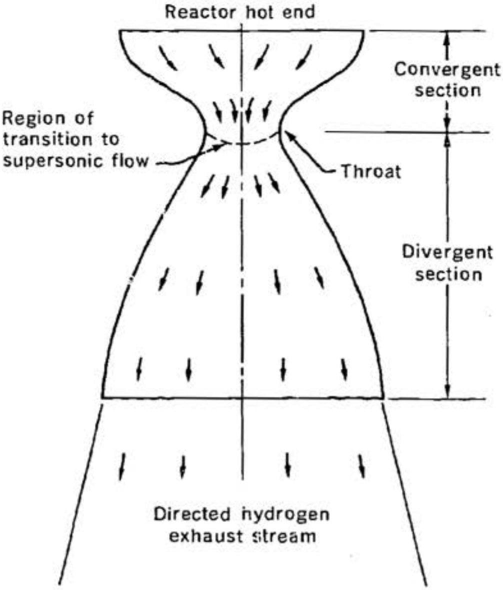
Where the Work is Done

The hydrogen leaving the hot end of the nuclear rocket reactor is laden with thermal energy that first must be converted into gas kinetic energy and then into rocket kinetic energy. This is the job of the nozzle. A constriction called the nozzle "throat" starts the process nicely. First the throat speeds up the hydrogen velocity until it is travelling at the speed of sound (Mach 1). Beyond the throat, the nozzle opens up into a carefully contoured "divergent" section. Here, the hydrogen expands and cools rapidly as heat energy is converted to gas velocity (kinetic energy). The hydrogen, now travelling at supersonic velocities, pushes against the divergent sides of the nozzle, pushing the rocket in the opposite direction through airless space. The expansion of hot gas in the nozzle is analogous to gas expansion against a piston or a turbine blade.



A possible method of diverting a small fraction of reactor power to drive the propellant pump is shown in this engine arrangement. This particular arrangement is called the "hot bleed cycle". Later, the so-called "full-flow cycle" which is used in the NERVA engine will be described.

To achieve a high exhaust velocity, the exit area of the divergent section must be as large as possible in comparison to the throat area. For booster rocket engines, the ratio of exit area to throat area is usually about 15 to 1. For space, the ratio can be as high as 100 to 1, limited only by the length and weight of the nozzle. Nozzle design



The rocket nozzle converts the heat in the exhaust gas to directed kinetic energy.

is a compromise between these factors to attain high exhaust velocity.

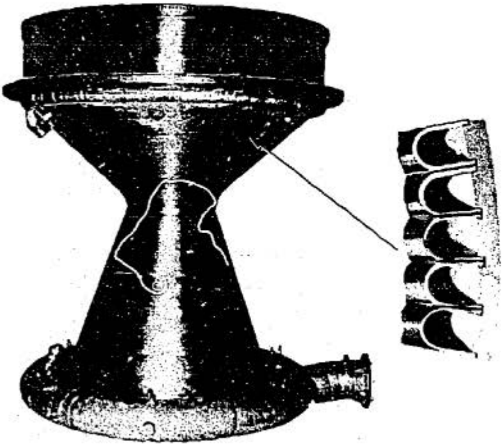
As the hydrogen leaves the end of the nozzle, it still contains some of the heat energy that the reactor added to it. This is "waste heat" and cannot be converted into the kinetic energy of the exhaust gas. Like all other engines that convert heat into kinetic energy, the nuclear rocket engine must throw away some of the heat it generates.

Powerful forces act on the nozzle because it has to carry the entire thrust load (37.5 tons in NERVA) up to the rocket body proper. What material can withstand this force in the presence of the super-hot hydrogen rushing past it at supersonic speeds? Graphite is too weak and steel would melt. Tungsten is probably strong enough, but no one yet knows how to fabricate big structures out of tungsten. The solution is a high temperature alloy such as stainless steel, covered by a solid phalanx of cooling tubes that keeps the nozzle temperatures well below the melting point of the

A nuclear rocket nozzle under construction, showing coolant tubes welded to the basic bell-shaped structure.

alloy. Rocket engineers call this a regeneratively cooled nozzle. Most liquid chemical rockets use this sort of nozzle, too.

In the chemical rocket, the nozzle coolant is usually the liquid fuel or oxidizer, which is diverted through the nozzles' cooling tubes on its way from the large fuel tanks to the combustion chamber. The nuclear rocket copies this

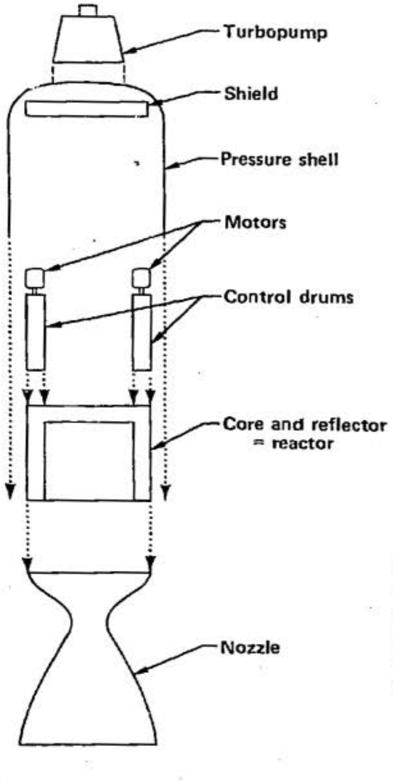


Structural details of a regeneratively cooled nozzle. Cross-section of nozzle "skin", showing the phalanx of hydrogen-carrying cooling tubes behind the high-temperature alloy surfaces is shown at right.

technique by pumping the supercold liquid hydrogen through the nozzle tubes, then up through the reactor reflector, and finally down through the core proper. Nozzle cooling thus forces a down-up-down hydrogen flow pattern. Without this cooling the nozzle would not survive more than a few seconds.

Holding the Pieces Together

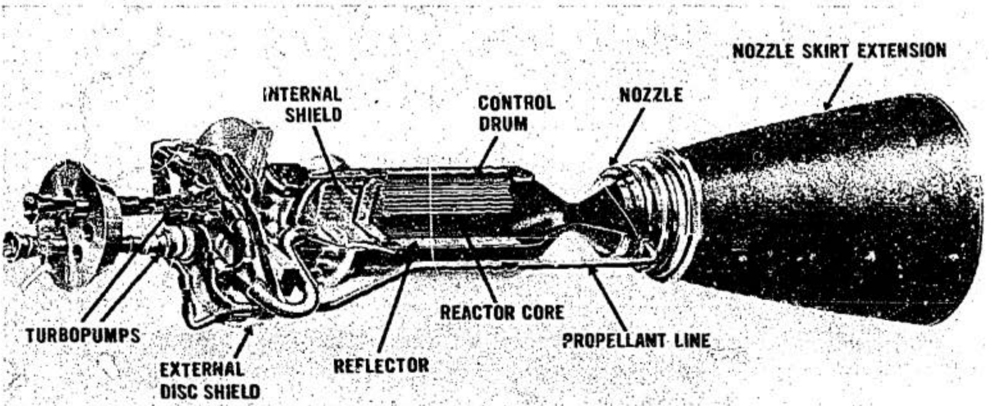
Holding the various pieces of the engine together is the obvious task of the engine structure. All major components are arranged along a centerline that extends from the nozzle, through reactor and turbopump, into the rocket body proper. The engine structure is essentially an exoskeleton (like a beetle's hard shell) built symmetrically around the



Exploded view of a nuclear rocket engine. Control drums fit in the reflector, the reactor inside the pressure shell, and the turbopump and nozzle go at top and bottom, respectively.

centerline. The nozzle is bolted to the reactor pressure shell, which in turn is bolted to a truncated conical shell that supports the turbopump. Thus, a continuous shell of strength encapsulates core, reflector, control drums, turbopump, and miscellaneous accessories.

A critical structural problem arises at the junction between the engine and rocket body, however. Across this junction must be transmitted the entire engine thrust that is conveyed upward from the nozzle through the engine exoskeleton. Ordinarily, such a joint would present no engineering difficulties. But in this case, the joint must be *flexible*. All big rockets have their engines mounted on gimbals that permit the "driver" to steer them. During a launch, for example, a gust of wind might deflect an ascending rocket off course: A gimballed engine can bring it back on the desired flight path. Gimballing chemical engines is relatively easy because they are lightweight. But, in a nuclear rocket, the heavy reactor replaces the empty combustion chamber of the chemical rocket. Despite the added weight, suitable flexible joints now have been designed.



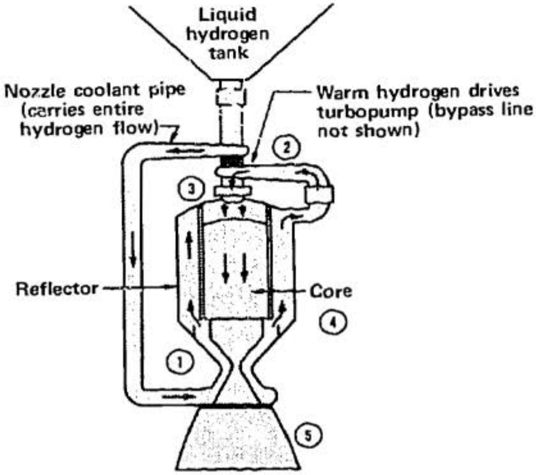
Drawing of the complete NERVA engine.

A final structural note: Heavy though the nuclear engine may be, it is still but a small appendage on a much larger structure consisting mainly of huge propellant tanks.

Bootstrapping and the Full-Flow Turbine Drive

The NERVA engine is really two engines in series. The main engine is, of course, the rocket nozzle that converts most of the energy in the *hot* hydrogen coming from the reactor proper into exhaust kinetic energy. The other engine is the turbopump, which extracts a portion of the energy in the *warm* hydrogen returning from cooling the nozzle and reflector and converts it into the rotary motion of the main hydrogen pump. Following the diagram on page 37, the sequence of events is: (1) the hydrogen steam picks up energy from the nozzle and reflector; (2) the turbine attached to the pump converts part of this energy into pump energy; (3) the hydrogen is pumped into the reactor; (4) the reactor adds energy to the hydrogen stream; and (5) the nozzle converts a fraction (90%) of the hydrogen energy into exhaust kinetic energy. The overall process is called the "full-flow" or "topping cycle" because there are two separate additions of energy to the hydrogen—one on top of the other. Some logical questions at this point are: How is engine thrust controlled and how can we get the engine started?

Suppose that some spaceship pilot of the future wants more thrust from his nuclear rocket engine, all he will have to do is pull a lever that partially closes a valve in a pipe that carries some of the warm hydrogen around the turbine driving the pump. When hydrogen flow is restricted in this "bypass line", more of the warm hydrogen passes through the turbine. The turbine now has more power to convert into pump power and consequently speeds up. Thus, more liquid hydrogen flows into the reactor for thrust production. But in a rocket engine, unless the reactor power is increased simultaneously, the only result will be *more, but cooler*, hydrogen leaving the reactor. At first



Hydrogen flow diagram in the full-flow cycle. The numbers refer to the description of the operation of this cycle on page 36.

glance one would think that the pilot should also signal the reactor control drums to raise the reactor power. It turns out, however, that this is unnecessary. Nuclear rocket control is simplified by the fact that the hydrogen itself affects reactor criticality because of its ability to collide with neutrons and slow them down to speeds where they can more readily cause uranium fissions.* In other words, shooting more hydrogen into the nuclear rocket core is equivalent to a slight outward rotation of the control drums. The pilot, then, by closing the valve in the turbine bypass line will effectively increase both hydrogen flow and reactor power with the same action. His lever will be as direct and simple as the throttle on an automobile engine.

But what keeps the reactor power from increasing indefinitely once the additional hydrogen is pumped in? (Remember that reactors are *rate-controlled* and that their power level keeps rising once neutron poisons are pulled

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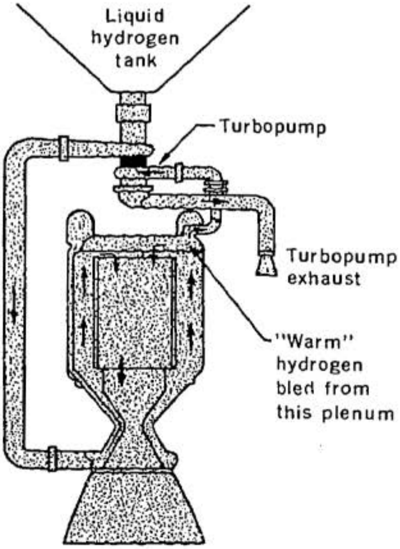
*The hydrogen thereby serves as a reactor moderator.

away from the core.) The answer to this also is simplicity itself: As the reactor power rises, so does the temperature of the hydrogen. The hydrogen expands with temperature, and there is less of it in the core at any one moment, even though it is being pumped through faster. Less hydrogen means that reactor criticality is affected less, and the power level begins to level off.

In fact, the power will become constant when the average hydrogen temperature is *exactly what it was before the pilot commanded the engine to provide more thrust.* Since temperature stabilizes at the old value, exhaust velocity, v, is unchanged. The things that have changed are $\dot{m}$, the hydrogen flow rate, and F, the thrust. Because $F = \dot{m}v$, the engine thrust is directly proportional to the flow rate (v is fixed because the temperature is fixed) and, $\dot{m}$ in turn, to how far the pilot closes the valve in the bypass line. In other words, the hydrogen gas in the core, by either expand-



Cold bleed cycle

A third type of engine cycle is the "cold bleed cycle". This mode of operation makes inefficient use of hydrogen propellant because some of it is thrown away.

ing or contracting, changes the reactor power in a way that keeps temperature constant. In reactor engineering, hydrogen is said to have a *negative temperature coefficient of reactivity*.

The full-flow turbine-drive cycle was selected over several other potential cycles because it yields the highest performance at a given reactor operating temperature. The other major contender was the *hot bleed cycle*, in which a small portion of the hot hydrogen rushing out of the reactor is fed back to the turbopump. The diverted hydrogen, after it has passed on some of its energy to the turbine, is jettisoned and does not produce useful thrust. The hot bleed cycle is therefore wasteful of hydrogen and, for the same reactor temperature, has a specific impulse* about 25 seconds lower than a topping cycle using the same reactor. Because the hot bleed cycle's turbine uses only a small fraction (about 3%) of the hydrogen stream, it is small and lightweight compared to the topping cycle turbine. It is, however, a high temperature turbine and subject to all the ills that befall hot, high-speed rotating machinery—in other words, its reliability would be lower than that of the bigger but cooler topping cycle turbine.

Engine designers also had to find a scheme that would start the engine, given a cold reactor and an inactive turbopump. The first thought is for some energy source to turn over the turbopump. In an automobile, a storage battery and starter motor suffice, but a similar system that was big enough to turn over the turbopump would weigh too much. The answer to the startup problem lies in the energy contained in the pressurized hydrogen in the propellant tank. Even the very cold liquid hydrogen, when admitted to the turbopump under pressure, can turn it over enough to push a little of the hydrogen into the reactor. Here the hydrogen picks up some heat and is turned to gas, which

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*Propulsion engineers often also speak of an artificial quantity called *specific impulse*, which is equal to the exhaust velocity divided by the acceleration due to gravity, g_0, (9.8 meters per second^2, or 32.2 feet per second^2). This is also equal to $F/g_0\dot{m}$.

drives the turbopump a little faster. The turbopump pumps more liquid hydrogen into the engine. More warmed hydrogen drives the turbopump faster, and so on, until full power is reached. The term "bootstrapping" is applied to this type of cold start, and the engine really does pull itself up to full power, in effect "by its own bootstraps".

The turbopump cycle, the structure, and the engine controls transcend any one of the other major components. They unify the engine subsystems and show that one part cannot be designed without careful regard for its effect on the rest.

NINETY MILES OUT IN THE DESERT

A four-lane dual highway runs northwest from Las Vegas, Nevada, toward Death Valley. After 90 miles of sand, rocks, Joshua trees, and creosote bush, the road abruptly narrows to two lanes. A few miles (kilometers) to the north are the AEC's Camp Mercury site for underground nuclear weapons testing* and the AEC–NASA Nuclear Rocket Development Station (NRDS). NRDS is surrounded by barren mountains and located in a flat basin, which is called Jackass Flats after some of the indigenous local inhabitants. Both reactors and complete engines can be tested safely at NRDS.

NRDS has three major test areas: Test Cells A and C plus Engine Test Stand No. 1 (ETS-1). The Kiwi, NERVA, and advanced Phoebus reactors have been put on trial at the two Test Cells. ETS-1 is reserved for engine experiments and NERVA engine firings. The three test areas are connected by road and railroad to the R-MAD and E-MAD Buildings (Reactor and Engine Maintenance, Assembly, and Disassembly). Typically, a reactor or engine is put together in one of the MAD buildings and then carried via the "Jackass and Western Railroad "(jokingly called the world's shortest and slowest) to one of the test sites. After the test, while the engine or reactor is still highly radioactive, a heavily shielded railroad engine tows it back to the proper MAD building for dissection. The map gives little feeling for the great distances between the test installations, MAD buildings, and other support facilities. An observer at any point in NRDS can see only minute outlines of the next building shimmering in the desert heat.

The ETS-1 is the most impressive structure at the station. It rises approximately 121 feet (37 meters) from the desert floor and looks like a structure that would be at home at Cape Kennedy. Although only engines—not complete rockets—are tested here, a heavy superstructure is

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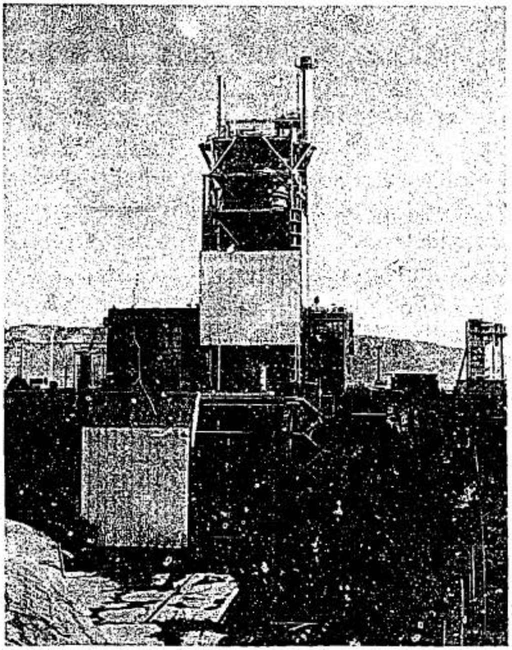
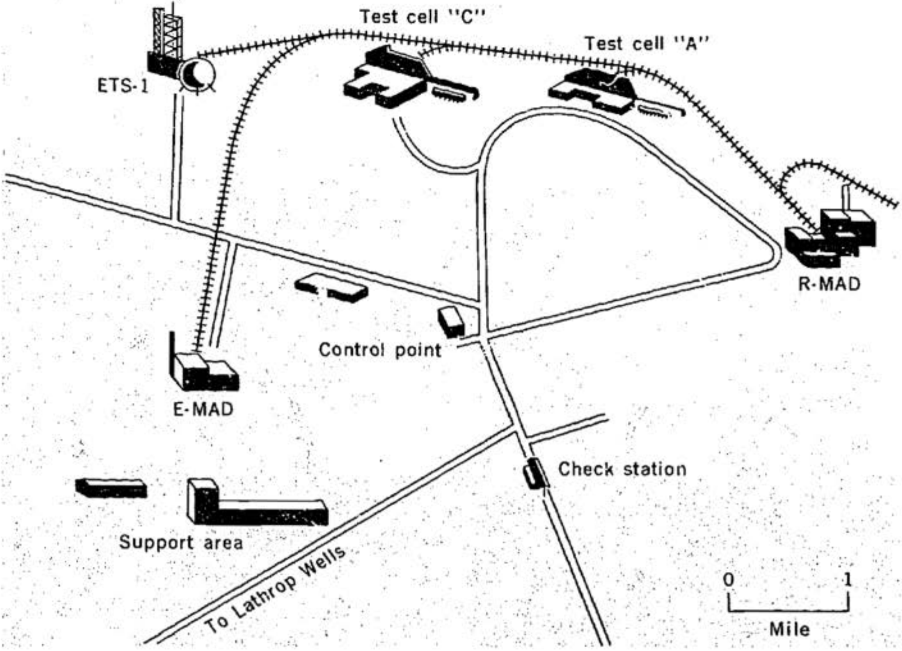
*See *Plowshare*, another booklet in this series, for an account of this testing. The name "Mercury" has no relation to the NASA "Project Mercury" for manned space flight; it perpetuates an old mercury-mining town name.

required to hold the big engine (one is about 7 meters long) in a vertical position and keep it from soaring off into space as its thrust builds up. A spherical thermos-like dewar (pronounced doo´-er) 14 meters in diameter, holding up to 260,000 gallons (1,000,000 liters) of liquid hydrogen, stands nearby as a substitute for the rocket propellant tanks that in flight would tower high over the relatively diminutive engine on the launch pad.

Beneath the engine nozzle is a large, water-cooled exhaust duct that turns the hydrogen stream by 90° and directs it down a concrete-lined artificial canyon. (The water is pumped up from deep wells.) During a test, this canyon becomes an inferno as the hot hydrogen spontaneously ignites upon contacting the air and burns to form water. Unlike the spectacular conflagration created during the firing of a kerosene-burning rocket, a nuclear rocket engine flame is invisible save for any incandescent impurities and the heat aberrations it produces in the air.



Engine Test Stand 1, from a different vantage that shows the exhaust deflector "canyon", foreground, incised in the desert floor to permit escape of burning hydrogen. Note upright semicylindrical shields on either side (near left, far right), which are moved around the engine while test is in progress.

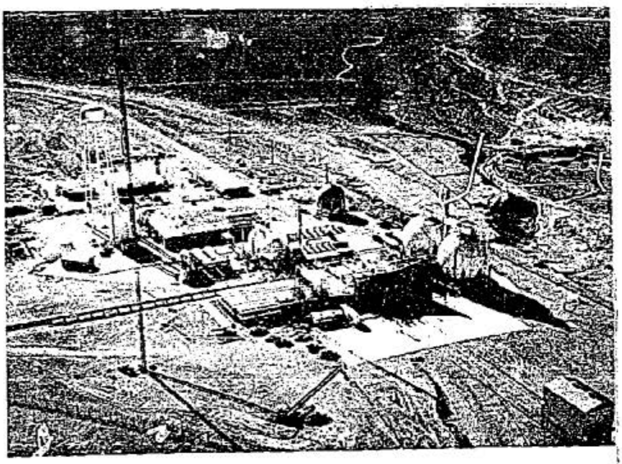


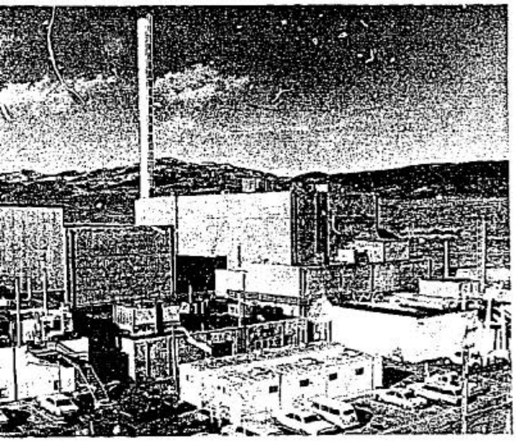
Arrangement of facilities at the Nuclear Rocket Development Station, Nevada.

All the Kiwis, Phoebuses, Pewees, and NRXs were tested on special railroad cars that carried them between the test cells and R-MAD and also served as mobile testbeds. Thrust and exhaust velocity were engine parameters of little interest in those reactor tests; actually, the nozzles were not designed to produce thrust efficiently. The results sought in testing a complete engine, though, dictate that the engine be placed in a special structure on the ETS-1 that can measure the reaction forces that are generated. A unique railroad car called the Engine Installation Vehicle (EIV) has been constructed to carry the complete engine up to the ETS-1 and lift it into place on the test stand with hydraulic "hands". After a test, the process is reversed and the hot engine is returned to E-MAD.

The MAD buildings are primarily immense "hot cells" where engineers can perform work on radioactive reactors and engines, but remain protected by thick concrete walls.

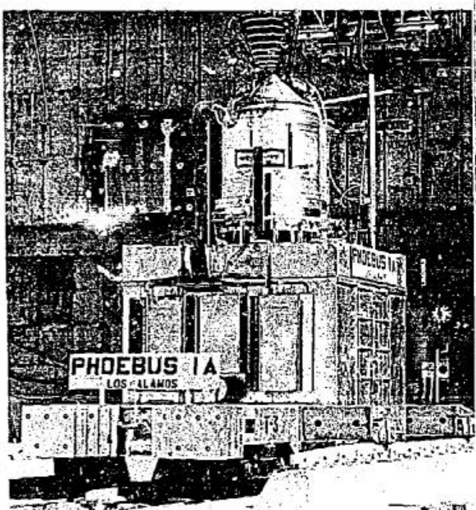
Test Cell C in 1967. Movable shields on test stand, right center, surround reactors during test. Building, lower right, can be moved on rails over reactors for weather protection.



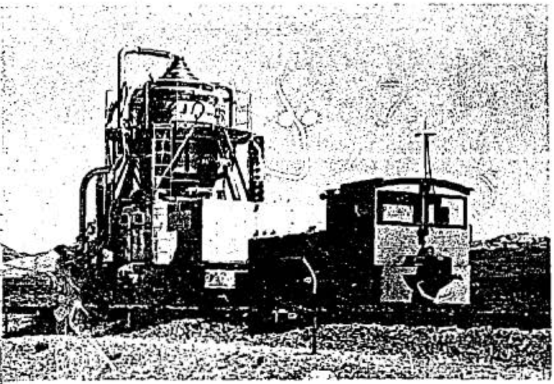


The E-MAD Building, where engines are put together, or disassembled after tests.

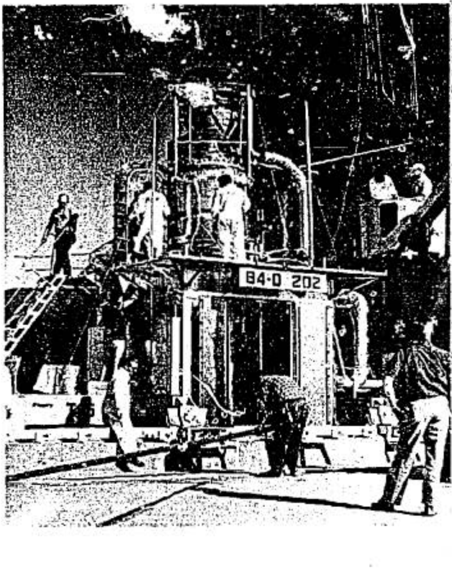
The Phoebus-1A reactor after arrival on its special railroad car at the test cell.



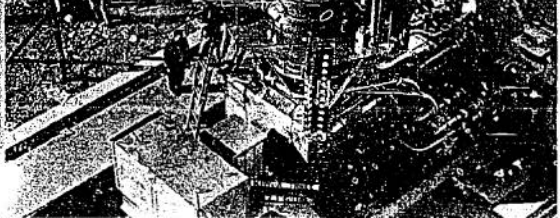
Nuclear Space Propulsion Tests



Moving a Kiwi reactor from its assembly bay to a test cell. This "Jackass & Western RR" locomotive can be remotely controlled.



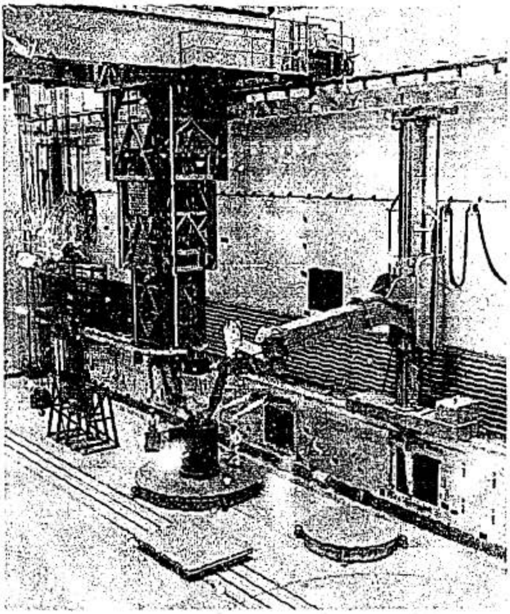
Workers swarm over a Kiwi-B reactor prior to its test in the series that established the value of liquid hydrogen propellant.



A Kiwi-A ready for a test with gaseous hydrogen propellant.

Once an engine or reactor has been placed in one of the cavernous "bays" in a MAD building, engineers can strip it down piece by piece with remote manipulators that simulate human arms and hands. The NERVA engine, for example, has several thousands of parts, including bolts, fuel elements, pipe connectors, etc., that all must be checked after a test.

Although this booklet concentrates attention on the nuclear rocket engine, the scope of NRDS facilities confirms the general rule of thumb that most of the money used in the space program stays right on terra firma in the form of launch pads, tracking facilities, research-and-development equipment and salaries, and, of course, NRDS. Success in space depends first of all upon success on the ground.



Interior of the E-MAD Building, showing the huge overhead and wall-mounted manipulators used for disassembling radioactive nuclear rocket engines. When in actual use, no workmen would be present in this portion of the building, because of the high radiation levels.

The Engine Installation Vehicle (EIV) carrying an engineering model of the NERVA engine. The shielded Manned Control Car (MCC), rear, propels the EIV along the NRDS railroad tracks.

ENGINES FOR THE MOON AND BEYOND

The big "selling" point of the nuclear rocket is its higher exhaust velocity, which is approximately double that of the best chemical rockets. But this advantage is partially offset by the fact that the nuclear engine is considerably heavier and more costly than a chemical engine of the same thrust rating. Admittedly, nuclear rocket engines are in an earlier stage of development than chemical engines, too. Comparing engine weights and costs at a fixed thrust level does not tell the whole story. The nuclear rocket's doubled exhaust velocity means that it uses only half as much propellant for each second of operation. Thus, the nuclear rocket can *do* much more than a chemical rocket with equal thrust. *How much more* depends a great deal upon the type of mission being contemplated.

NERVA's thrust of 37.5 tons is considerably smaller than that of the biggest chemical rockets, which can generate as much as 750 tons each. The role of the nuclear rocket is not in journeys beginning at the launch pad, where chemical engines have been so highly successful, but rather in outer space where the nuclear rocket's high exhaust velocity is a great asset. We should think of nuclear rockets then, as prime movers for missions beginning *from an earth orbit* and moving outward toward higher earth orbits, the moon, and the planets. Very high thrust levels are not necessary for nuclear rockets because they are not required to lift payloads off the launch pad.

The great propellant economy of the nuclear rocket tends to make it superior for those missions in which much of the spacecraft mass is allotted to propellant. This is subject to the condition that the payload mass be a sizeable fraction of the engine mass, otherwise the advantage conferred by the higher exhaust velocity would be negated to a large extent by the nuclear engine's 12-ton mass. Neither would the nuclear rocket be the best engine where only small velocity changes are desired, such as in the maneuvering of an orbital space station. But large-scale orbital maneuvers, fast trips to the outer planets, the delivery of payloads to the surfaces of, or orbits about, Venus, Mars, Jupiter, and the other denizens of the solar system, and the large-scale ferrying of supplies to the moon are right down the nuclear rocket's [illegible] Generally speaking, the more "ambitious" the mission, the better the nuclear rocket looks.

Nuclear rockets are an integral and indispensable part of the *space transportation system* that has been proposed for America's space ventures following the completion of the Apollo program. The "first stage" of this system is the chemical rocket. Launch vehicles, such as those in the Saturn class or the proposed new space shuttle, will use chemical energy to boost payloads into low earth orbits; nuclear stages, already in space, will pick up these payloads and carry them—with low propellant consumption (equivalent to low cost)—to their final destinations. The NERVA engine is the only practical advanced propulsion system that can meet the requirements of the space transportation system in the 1980s and beyond.

A Space Transportation System. Lunar operations beyond Apollo may involve the establishment of permanent or semipermanent bases on the moon. Obviously, a great deal of hardware would have to be injected into earth orbit and then ferried to the moon by the space transportation system. A NERVA-powered vehicle with a usable propellant capacity of 150 tons (distributed in eight propellant modules, as illustrated in the figure) could support a modest program of manned lunar exploration with six round trips per year. The nuclear shuttle could carry 60 tons of payload on the outward leg and return with 13 tons. The total shuttle weight prior to its departure for the moon would be about 250 tons. An equivalent, two-stage shuttle with chemical rockets would weigh about 350 tons in earth orbit. In support of various other manned and unmanned space missions, the NERVA-propelled vehicle could transport from 5 to 60 tons from a low earth orbit to a synchronous orbit almost six earth radii above the earth's surface.

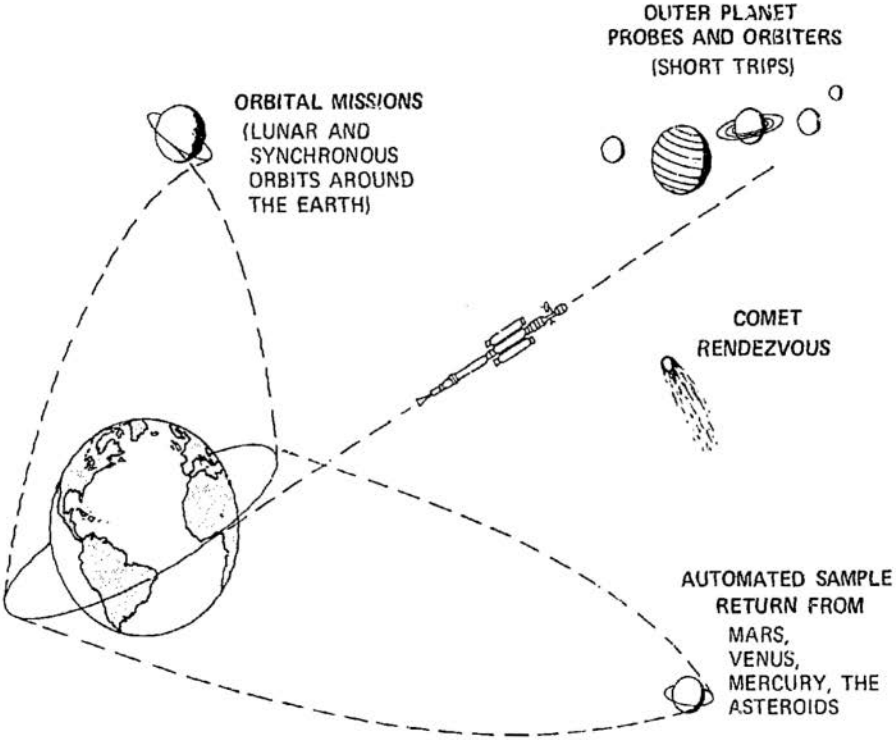
Automated spacecraft will be man's precursors to Mars, Jupiter, and targets beyond. Here, too, the nuclear rocket's high specific impulse gives it an advantage over the chemical rocket. The basic NERVA engine can be applied to many different solar-system missions by simply adding or subtracting propellant tanks to and from the spacecraft.

A particularly interesting mission in the next decade or two will involve the automated collection and return of geological and possibly biological samples from Mars by an unmanned spacecraft. A nuclear-propelled spacecraft with five standard propellant tanks could deliver 17 to 32 tons to an orbit about Mars beginning from a low earth orbit. With this kind of payload, 160 to 240 pounds (73 to 110 kg) of samples could be selected by a roving automaton and then returned to earth. Sample-return missions to Mercury, Venus, and the asteroids are also possible with nuclear spacecraft. Such automated missions would be far cheaper than long, complex manned missions.

The superlative propulsion capabilities of the nuclear rocket can be applied to reducing travel time to the planets as well as increasing the payloads. Shorter, high-energy trajectories could cut a year or two off trip times to the outer planets. Time savings such as these may be critical on long missions where the reliability of complex spacecraft is being pushed to its upper limits.

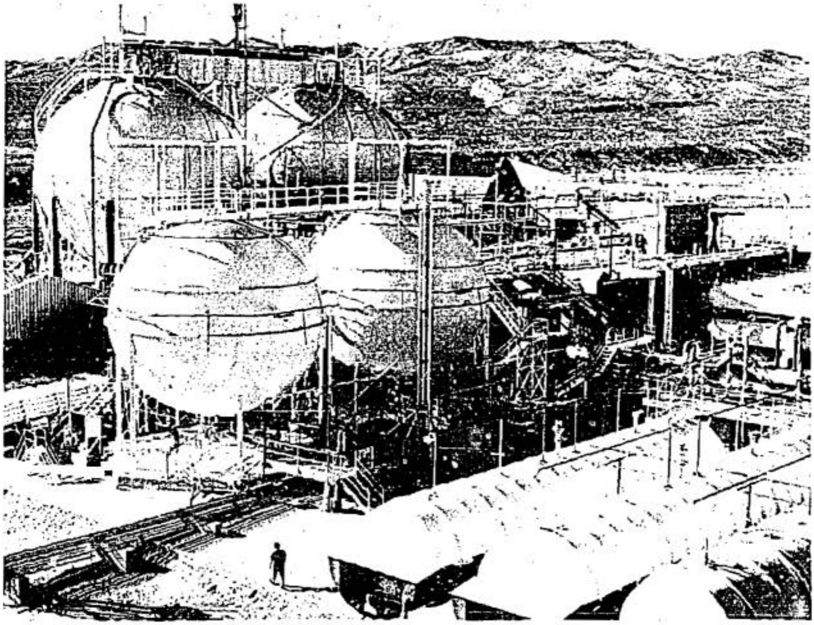
A final bonus derived from nuclear rocket propulsion arises from the tremendous quantity of potential energy locked in the uranium-235 in the reactor core. Only a small fraction of this energy is used in engine operations. By inserting separate coolant loops in the reactor, some of this unused energy can be tapped to generate electricity. Power levels of 15 to 25 kilowatts could easily be generated for long periods of time. Large quantities of electrical power are just as essential to the exploration of the solar system as the high-performance nuclear rocket engine.

In all these classes of missions, it is the high exhaust velocity of the nuclear rocket that confers superiority. Of course, if the nuclear engines on a lunar ferry were employed on many round trips, the second major advantage of the nuclear rocket, high-energy density in the reactor core (see p. 8), may also come to the fore. Lastly, the same type of modular nuclear stage could, of course, undertake *all* types of missions, promoting system standardization.



Typical mission for the NERVA engine beyond terrestrial orbit.

Despite the superiority indicated in these particular missions, the real significance of the nuclear rocket lies in the fact that it represents a true advance in our overall propulsion capability; perhaps as big a jump as the first automobiles were over the horse. We can only surmise where such an advance in propulsion capability eventually will take us.



Giant dewars containing liquid hydrogen and liquid oxygen and a maze of pipes, valves, and other equipment are needed for the reactor t[illegible]his is Test Cell C at NRDS.

GLOSSARY OF ACRONYMS AND CODE NAMES

AEC	Atomic Energy Commission.
ANP	Aircraft Nuclear Propulsion program.
Atlas	An Air Force ICBM using kerosene and liquid oxygen propellants.
Centaur	A chemical rocket system intended for unmanned space missions, burning liquid hydrogen–liquid oxygen.
Condor	Early code name for the nuclear rocket; also the name of an early committee studying nuclear rockets.
Dumbo	An early experimental rocket reactor.
EIV	Engine Installation Vehicle at NRDS.
E-MAD	Engine-Maintenance, Assembly, and Disassembly building, at NRDS.
EST	Engine System Test.
ETS-1	Engine Test Stand 1 at NRDS.
ICBM	Intercontinental Ballistic Missile.
Kiwi	A series of rocket test reactors built by Los Alamos Scientific Laboratory.
LASL	Los Alamos Scientific Laboratory in New Mexico.
MCC	Manned Control Car, prime mover for the EIV, at NRDS.
NASA	National Aeronautics and Space Administration.
NERVA	Nuclear Engine for Rocket Vehicle Application, an AEC–NASA program.
NRDS	Nuclear Rocket Development Station in Nevada.
NRTS	National Reactor Testing Station in Idaho.
NRX	NERVA Reactor Experiment.
NTS	Nevada Test Site, including NRDS.
Orion	Nuclear bomb propulsion study; now discontinued.
Peewee	A reactor for testing nuclear rocket fuel elements.
Phoebus	An advanced series of nuclear rocket reactor experiments under development at LASL.
Pluto	Program for developing nuclear ram-jet propulsion; now discontinued.
Poodle	A very small nuclear rocket concept employing decaying radioisotopes as the heat source.
RIFT	Reactor In-Flight Test program; now discontinued.
R-MAD	Reactor-Maintenance, Assembly, and Disassembly building at NRDS.
Rover	General name for the U. S. nuclear rocket program.
Saturn-5	The key launch vehicle for NASA's manned moon exploration system, powered by clustered liquid oxygen–liquid hydrogen engines.
SNPO	Space Nuclear Propulsion Office, a joint NASA–AEC organization.
TNT	Transient Nuclear Test.
XE	Ground experimental engine.

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Fundamentals of Nuclear Flight, Robert W. Bussard and Richard D. DeLauer, McGraw-Hill Book Company, New York, 1965, 453 pp., $15.50.

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Astronautics and Aeronautics, 3 (June 1965). Several articles of interest.

Beyond Apollo with Nuclear Propulsion, Paul G. Johnson, *Astronautics and Aeronautics*, 2: 22 (December 1964).

Motion Pictures

Available for loan without charge from the AEC Headquarters Film Library, Division of Public Information, U. S. Atomic Energy Commission, Washington, D. C. 20545 and from other AEC film libraries.

Power for Propulsion, 15 minutes, color, 1965. Produced by Aerojet-General Corporation. Major steps in the history of power sources for propulsion are traced. Animation sequences are used to illustrate the principles of rocketry, Newton's Law of Motion, and operation of nuclear rocket engines. Development of NERVA is covered, including its first test firing at the testing station in Jackass Flats, Nevada. Developments for deep-space missions to the moon and beyond are shown.

Project Rover, 21½ minutes, color, 1963. Produced by the AEC's Los Alamos Scientific Laboratory. This is a 1962 progress report on Project Rover, a program to develop a nuclear rocket for spacecraft propulsion. Design, fabrication, and testing of a Kiwi are detailed.

Atomic Energy for Space, 17 minutes, color, 1967. Produced by the Handel Film Corporation with the cooperation of the AEC and NASA. This film explains the two basic ways in which nuclear energy for space is being developed: A nuclear rocket for space propulsion, and isotopic generators and reactor power plants to produce electricity for spacecraft operations. Project Rover is covered through animation and film shots of Kiwi and NERVA tests. The efficiencies of nuclear and chemical rockets are compared. The last part of the film discusses the SNAP (Systems for Nuclear Auxiliary Power) program.

Nuclear Propulsion in Space, 19 minutes, color, 1969. Produced by the National Aeronautics and Space Administration and the AEC. This film presents the story of the development of a nuclear rocket engine for space exploration. Conventional chemical rockets are compared with nuclear rockets through the use of graphs, charts, and animation that show that the nuclear rocket can be twice as efficient as its chemical counterpart. The film explains the principles and operating characteristics of a nuclear rocket and how its power and thrust will be controlled. Tests are shown of the KIWI reactor in Nevada and the NERVA (Nuclear Engine for Rocket Vehicle Application), which will complete the technology for a nuclear rocket engine application in space missions of the late 1970s and 1980s.

PHOTO CREDITS

Frontispiece courtesy Nuclear Rocket Development Station (NRDS)

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FRANCIS C. SCHWENK has 20 years experience in aeronautical and space propulsion research and development—the last 11 years in the Nuclear Rocket Program. In his present position of Assistant Manager for Vehicles and Propulsion Technology in the AEC–NASA Space Nuclea Systems Office, he is responsible for programs on nuclear r ket stages, advanced propulsion research, and applications stu . Mr. Schwenk received a B.S. degree from the Pennsylvania St University and an M.S. degree from the University of Illinc oth in the field of mechanical engineering. While at the NACA wis Flight Propulsion Laboratory, he authored many technical re arch reports on compressors for turbojet engines and receiv additional education in nuclear physics and reactor engineerin . When the National Aeronautics and Space Administration was formed, he served in the NASA headquarters office, planning for development of launch vehicles for space missions. He was coauthor with M. W. Rosen of the 1959 article, "A Rocket for Manned Lunar Exploration" (IRE Transactions, December 1969), which first described the basic characteristics of a lunar mission—later to become Apollo, and coauthor with E. W. Hall of "Current Trends in Large Booster Development", (*Aerospace Engineering,* May 1960). Since joining the Nuclear Rocket Program, he has written numerous articles and speeches, the most recent being "Prospects for High-Thrust Nuclear Propulsion Systems" with C. E. Franklin (Chemical Propulsion Information Agency).

THE AUTHOR

William R. Corliss is an atomic energy consultant and writer with 12 years of industrial experience including service as Director of Advanced Programs for the Martin Company's Nuclear Division. Prior industrial connections were with the Flight Propulsion Laboratory of the General Electric Company and with Pratt & Whitney Aircraft Company. Mr. Corliss has B.S. and M.S. degrees in Physics from Rensselaer Polytechnic Institute and the University of Colorado, respectively. He has taught at those two institutions and at the University of Wisconsin. He is the author of *Propulsion Systems for Space Flight* (McGraw-Hill 1960), *Space Probes and Planetary Exploration* (Van Nostrand 1965), *Scientific Satellites* (Government Printing Office, 1967). *Mysteries of the Universe* (Crowell, 1967), *Mysteries Beneath the Sea* (Crowell, 1970), and coauthor of *Radioisotopic Power Generation* (Prentice-Hall, 1964), *Human Factors Applications in Teleoperator Design and Operation* (Wiley, 1971), and *Man and Atom* (Dutton, 1971), as well as numerous articles and papers for technical journals and conferences. In this series he has written *Neutron Activation Analysis, Power Reactors in Small Packages, Direct Conversion of Energy, Computers, Nuclear Propulsion for Space, Space Radiation,* and was coauthor of *Power from Radioisotopes*.

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