PLENARY SESSION I

SPACE NUCLEAR SYSTEMS AND APPLICATIONS

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SPACE NUCLEAR PROPULSION SYSTEMS AND APPLICATIONS

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The basic principles of the operation of a nuclear rocket engine are reviewed along with a summary of the early history. In addition, the technology status in the nuclear rocket program for development of the flight-rated NERVA engine is described, and applications for this 75,000-pound-thrust engine and the results of nuclear stage studies are presented. Advanced research and supporting technology activities in the nuclear rocket program are also summarized.

INTRODUCTION

In presenting a paper on Space Nuclear Propulsion Systems and Applications for this National Symposium on Natural and Manmade Radiation in Space, I am going to assume that general remarks describing a nuclear rocket engine would give a valuable perspective for this distinguished audience of specialists in many fields. In addition, I will review the nuclear rocket program and discuss the use of the NERVA nuclear rocket engine in space flight missions.

Let me summarize a few important points before discussing details. For 15 years or so, the nuclear rocket program has been engaged in providing the necessary technology for development of the initial nuclear engine for flight. This engine is known as NERVA. Based on a successful technology program, the development of NERVA was initiated in 1969 and received limited funding for two fiscal years, 1970 and 1971. At this time in history, March 1, 1971, the budget for FY 1972 proposed by the Administration contains a rather low funding level for the nuclear rocket program, and the NERVA program and other important activities must be cut back substantially. It is important to realize that development of the NERVA engine is to be continued. Although maintained at a much reduced pace, we will try to retain some of the program capability and to make progress on essential areas of a very important, versatile, and useful propulsion system for a variety of space missions of the future. The budgetary problem stems from the limited resources allocated for advanced technology activities and the Space program and the need for funds in near term missions. This situation is summed up by a statement released by George Low, Acting NASA Administrator: "There is a need for the NERVA program. This need exists because nuclear propulsion represents a major breakthrough in the efficiency of space propulsion; and because many advanced space missions depend on this. But there is not a need to proceed with the full development of NERVA now. There are many programs that must be done before the capabilities represented by NERVA can be used -- these are the programs that are in our budget for FY 1972."

DESCRIPTION OF THE NUCLEAR ROCKET ENGINE

The essential features of a nuclear rocket engine system are shown in figure 1. After the liquid hydrogen propellant is pumped from storage in the rocket vehicle, it flows through the double-walled jet nozzle and the reflector to cool these components. Appropriately designed passages guide the hydrogen through the turbine to drive the pump, through an internal shadow shield, and through the hot fuel elements of the solid reactor core. Fuel elements, containing uranium-235, are heated by the energy released during fission. This energy is transferred to the hydrogen which is accelerated to high velocities as it flows through the jet nozzle to produce the desired thrust.

Nuclear rockets offer performance advantages over chemical rockets because a nuclear rocket has a specific impulse approximately two or more times that of a high-energy chemical system. While nuclear rocket engines are heavier than equivalent-thrust chemical rockets and while the propellant tankage of a nuclear stage tends to be larger because of the use of the low-density hydrogen propellant, these penalties do not compromise the gains derived from the high specific impulse of nuclear rockets. In general, the net effect is a nuclear advantage of about 50% or more per stage for missions of moderate energy and over 100% for high-energy missions. These gains are possible for the initial nuclear rocket engine; greater gains can be expected with advanced propulsion concepts.

This description of a nuclear rocket engine highlights certain important features that have set the course for the program to date. In order to achieve the

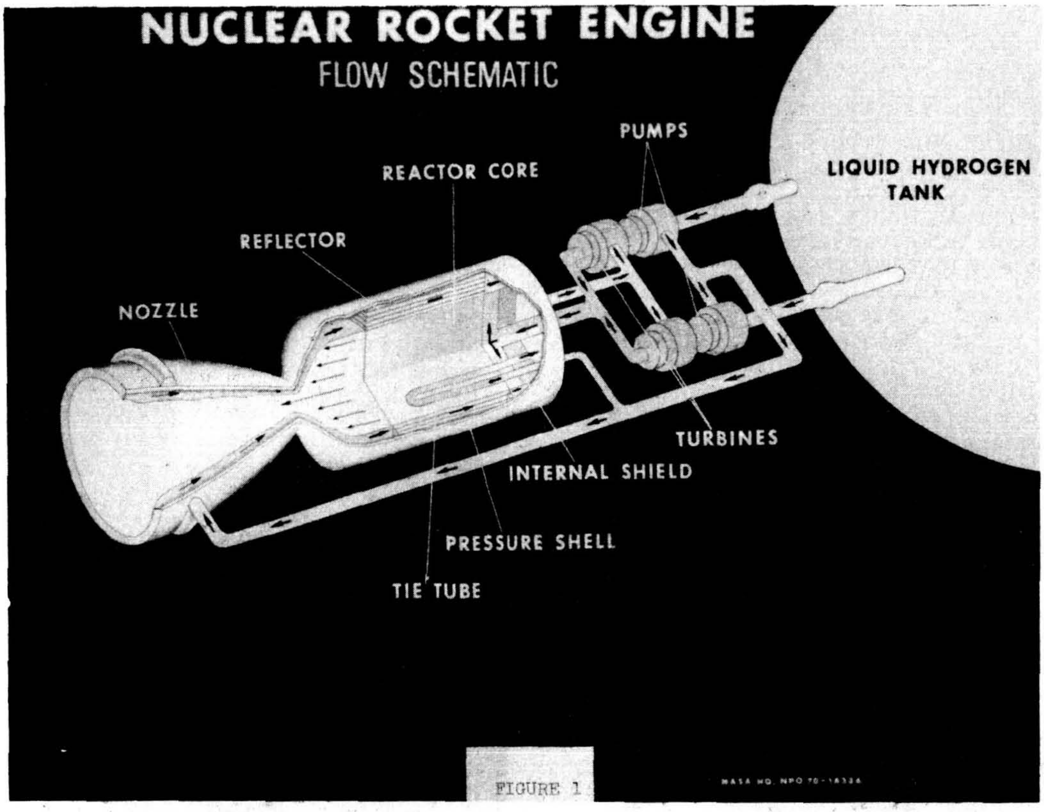


FIGURE 1

desired high specific impulse, the reactor must heat hydrogen to very high temperatures, approximately 4000°F for a specific impulse of 825 seconds. (Rocket engines that consume hydrogen-oxygen propellant can reach specific impulse values of 460 seconds.) Therefore, the rocket reactor must be constructed of a high temperature material having an appropriately low neutron absorption cross-section. The reactor must be compact to conserve weight; however, the structural design must permit the extraction of large quantities of power from the mass of the reactor. To gain some perspective as to the magnitude of the reactor design problem, consider that a rocket reactor produces 1500 Megawatts in a volume not much larger than an office desk. During every minute of operation, the reactor heats a 3-ton-per-minute flood of hydrogen from a temperature of -300°F to 4000°F. At operating conditions the reactor material glows with a white heat like that of the filament in an incandescent lamp.

The material initially chosen for this rigorous service in a rocket reactor is graphite. This material has desirable nuclear properties and, more importantly, retains mechanical strength at extremely high temperatures. Graphite, at the elevated temperatures required, reacts readily with hydrogen at a rate that would completely destroy the reactor in a few minutes unless some form of corrosion protection is provided. The necessary protection is supplied by metal carbide coatings that allow required reactor lifetimes to be achieved in tests at rated conditions as shall be discussed.

In addition to a high performance reactor, the nuclear rocket program had to pioneer in cryogenic engineering, development of liquid hydrogen turbopumps, fabrication of rocket nozzles and, generally, unite liquid rocket engine technology with nuclear technology to provide the basis for NERVA engine development.

HISTORY

Having described a nuclear rocket engine, we can now move on to a brief history of the program which has provided the basis for development of a flight-rated nuclear rocket engine. Additional information on the operation of the nuclear rocket and the history of the program are contained in reference 1.

Program Initiation & Technology Phases

A joint AEC-Air Force nuclear rocket program, known as ROVER, was initiated in 1955 at the AEC's Los Alamos Scientific Laboratory and Lawrence Radiation Laboratory as a result of an interest in considering nuclear rockets for long-range missiles. When it was decided that nuclear rockets were not required for missiles, the nuclear rocket program was continued for later application to space missions. In March 1957, the Los Alamos Scientific Laboratory (LASL) was selected as the single AEC laboratory for the nuclear rocket program and Lawrence Radiation Laboratory was assigned the responsibility for research on nuclear ramjet propulsion.

In October 1958, upon the establishment of the National Aeronautics and Space Administration, Air Force responsibilities for ROVER were transferred to the new agency in keeping with the dominant space role expected for nuclear rockets. The NASA Administrator stated the view that the ROVER program should proceed as fast as the technology would allow and NASA continued the development, initiated by the Air Force, of the hydrogen turbopump required for the KIWI reactor tests. (The name KIWI was taken from the flightless bird, Apteryx australis, of New Zealand, because these reactors were not intended for flight systems.)

The program initiation phase of the nuclear rocket program was highlighted by the KIWI-A series of proof-of-principle reactor tests conducted at the Nevada Test Site by LASL. Figure 2 shows the size of the KIWI-A reactor in relation to other reactors designed at LASL. These tests were as follows:

1959 - KIWI-A Reactor: Operated for 5 minutes at a power level of 70 Megawatts at high temperature.

1960 - KIWI-A Prime: Operated for 3 minutes at 85 Megawatts.

KIWI-A3: Operated for 5 minutes at 100 Megawatts.

The KIWI-A series of reactor tests gave data on reactor design and control and demonstrated the value of carbide coatings for protection of graphite from corrosion against the hot hydrogen propellant.

Another important step was the establishment in 1960 of the joint AEC-NASA Space Nuclear Propulsion Office for management of all nuclear rocket propulsive activities in both agencies. The name of this organization was changed to the Space Nuclear Systems Office in 1970 in recognition of its expanded responsibility for nuclear power as well as propulsion.

In May 1961, President John F. Kennedy, in an announcement that established the Apollo program as a national goal, recommended development of nuclear rocket propulsion technology and requested Congress to add $30 million to the FY 1962 ROVER program budget. The NERVA (Nuclear Engine for Rocket Vehicle Application) project was born and NASA and AEC awarded a contract to Aerojet-General and Westinghouse for the development of the Los Alamos KIWI-B reactor into a NERVA nuclear rocket engine for flight applications.

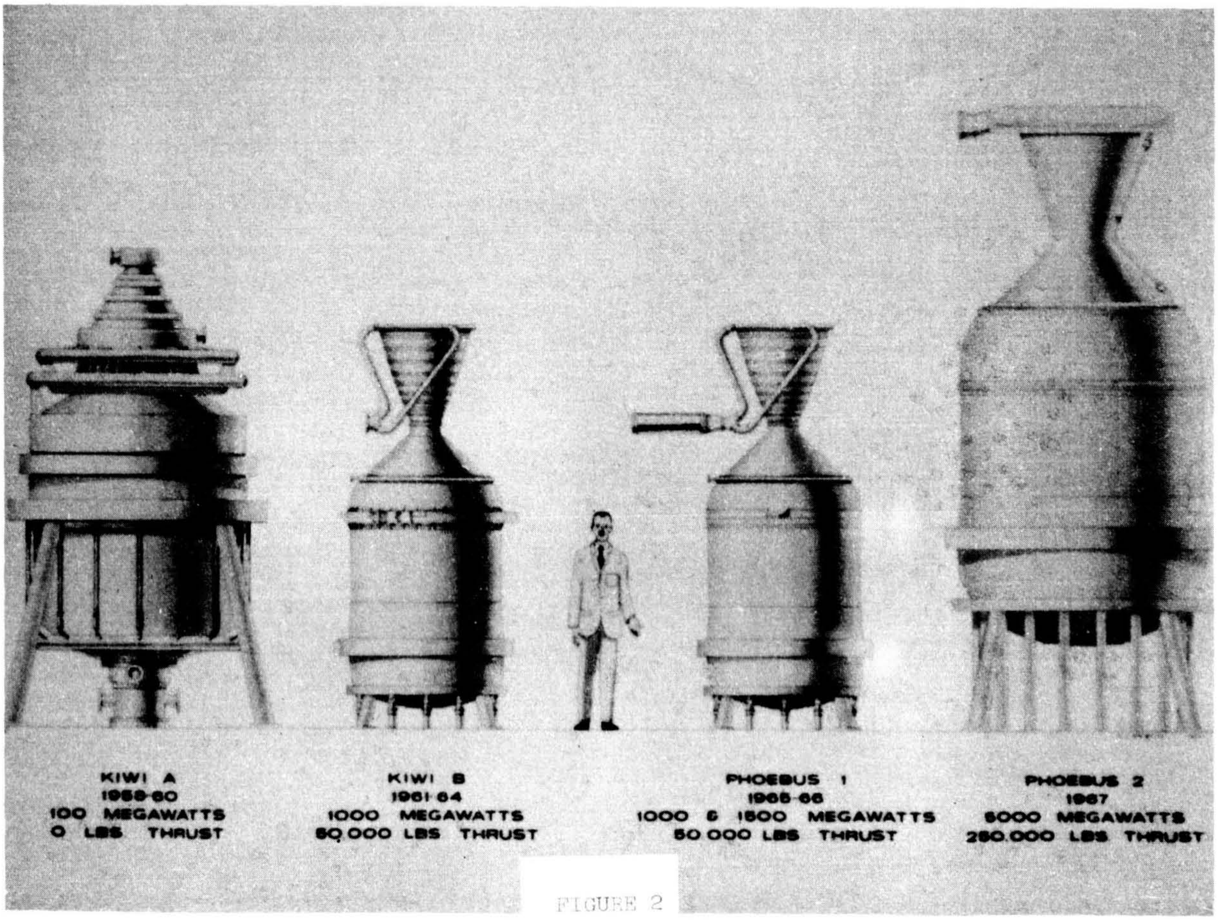


FIGURE 2

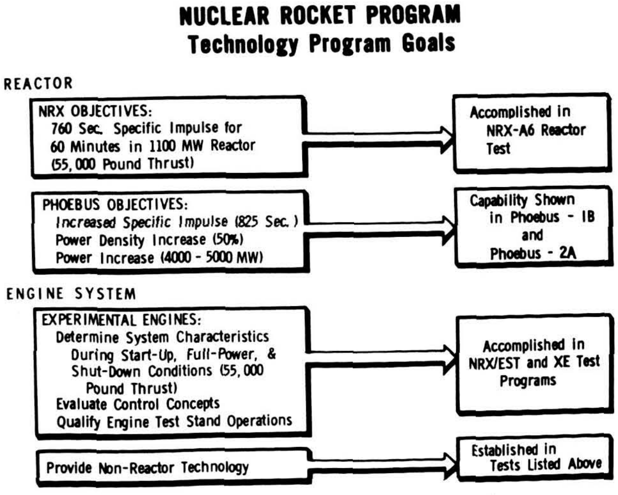
Late in 1961 the first of the KIWI-B series of reactors was tested at the Nuclear Rocket Development Station (NRDS) by LASL. This series of reactors was intended to examine, more specifically, design features that would be required in a flight system and to obtain experience with operation on liquid hydrogen. A second KIWI-B reactor test, KIWI-B1B, showed that rocket reactors could be stably operated with liquid hydrogen at high pressures, high-power levels and high-flow rates. This test was followed by a test of a flight-type reactor designated KIWI-B4A which suffered a structural failure later proven to be caused by mechanical vibrations induced by the flow of hydrogen in the reactor core. Further "hot" reactor testing was postponed until solutions to these structural problems were found as demonstrated by the recent history of the nuclear rocket program.

In the early 1960's a set of objectives was established to define the needed output for a program to establish the basic technology of the nuclear rocket. These objectives of the technology phase of the program are shown in figure 3. In the reactor area we had two sets of objectives. The first set was to achieve 760-seconds of specific impulse (Isp) with an endurance of an hour at 1100 Megawatts power. In addition, we set goals of higher performance to be achieved, if technology permitted, of up to 825-seconds Isp and increases in endurance, power-density and power-level up to more than 4000 Megawatts. The engine system objectives encompassed the total known needs for operational characteristics, control and performance. In addition we had to assure that necessary non-nuclear technology, in such things as pumps, valves and other hardware was available. In August of 1969, we completed this program when the tests of a ground experimental engine (to be discussed later) fulfilled its objectives.

Since the end of 1963, the nuclear rocket program has operated successfully 10 reactors, a breadboard engine system labeled NRX/EST, and a ground-experimental engine (XE). Figure 4 is a list of major test events in this program. Among the 10 different reactors were reactors operated at 500, 1100, 1500, and 4200 Megawatts of thermal power, covering a spectrum of design possibilities. As shown on figure 5, the testing program has accumulated more than 14 hours of operation, of which, over four were at or near full design power. Restart was demonstrated in reactor tests; the NRX/EST was started 10 times, the XE, 28 times. Fuel-element performance, as demonstrated in the laboratory, has been extended from 1964's 10-minutes endurance to a point at which now several elements have operated 600 minutes with 60 cycles. As a result of these efforts, the reliability and operational stability of nuclear rockets have been shown to be very high, with a successful record of operations as planned. In the process of gaining this experience, large amounts of design data have been accumulated and varying design concepts examined.

Ground Experimental Engine (XE) Technology

In addition to reactor activities, the technology program also has had the objective of understanding the characteristics of an integrated engine system. This aim was partly accomplished in the breadboard-engine system test program (NRX/EST) conducted in 1966 in reactor Test Cell A at the Nuclear Rocket Development Station and completed with the testing of the Ground Experimental Engine (XE) using the Engine Test Stand, ETS-1, at NRDS.



NUCLEAR ROCKET PROGRAM
Technology Program Goals

REACTOR

NRX OBJECTIVES:
760 Sec. Specific Impulse for
60 Minutes in 1100 MW Reactor
(55,000 Pound Thrust)

Accomplished in
NRX-A6 Reactor
Test

PHOEBUS OBJECTIVES:
Increased Specific Impulse (825 Sec.)
Power Density Increase (50%)
Power Increase (4000 - 5000 MW)

Capability Shown
in Phoebus - 1B
and
Phoebus - 2A

ENGINE SYSTEM

EXPERIMENTAL ENGINES:
Determine System Characteristics
During Start-Up, Full-Power, &
Shut-Down Conditions (55,000
Pound Thrust)
Evaluate Control Concepts
Qualify Engine Test Stand Operations

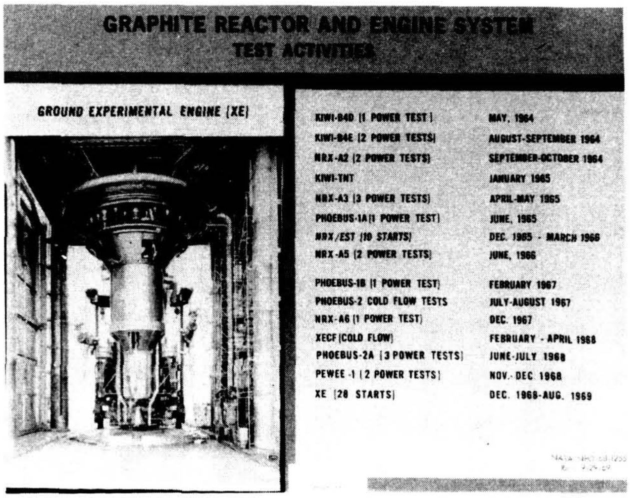
Accomplished in
NRX/EST and XE Test
Programs

Provide Non-Reactor Technology

Established in
Tests Listed Above

NASA HQ NPO70-15587 11-24-69

FIGURE 3



GRAPHITE REACTOR AND ENGINE SYSTEM
TEST ACTIVITIES

KIWI-B4D (1 POWER TEST)	MAY, 1964
KIWI-B4E (2 POWER TESTS)	AUGUST-SEPTEMBER 1964
NRX-A2 (2 POWER TESTS)	SEPTEMBER-OCTOBER 1964
KIWI-TNT	JANUARY 1965
NRX-A3 (3 POWER TESTS)	APRIL-MAY 1965
PHOEBUS-1A (1 POWER TEST)	JUNE, 1965
NRX/EST (10 STARTS)	DEC. 1965 - MARCH 1966
NRX-A5 (2 POWER TESTS)	JUNE, 1966
PHOEBUS-1B (1 POWER TEST)	FEBRUARY 1967
PHOEBUS-2 COLD FLOW TESTS	JULY-AUGUST 1967
NRX-A6 (1 POWER TEST)	DEC. 1967
XECF (COLD FLOW)	FEBRUARY - APRIL 1968
PHOEBUS-2A (3 POWER TESTS)	JUNE-JULY 1968
PEWEE-1 (2 POWER TESTS)	NOV.-DEC 1968
XE (28 STARTS)	DEC. 1968-AUG. 1969

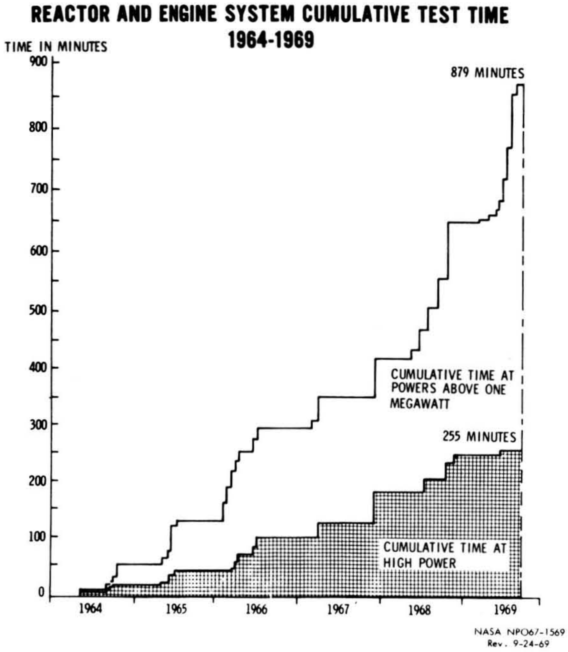


FIGURE 5

Figure 6 is a comparison of the XE configuration with that of the breadboard-engine system test (NRX/EST). The fundamental characteristics of both these systems are the same; the reactor, turbine, pump, nozzle, lines and valves are quite similar. However, in the XE engine, these components are arranged in a configuration closer to that of a flight system, and the use of a closely-coupled liquid-hydrogen run tank and the operation in a partially evacuated test compartment are new aspects of the XE test in ETS-1. All of these features reflect a closer simulation of the conditions which are expected to play a role in NERVA development.

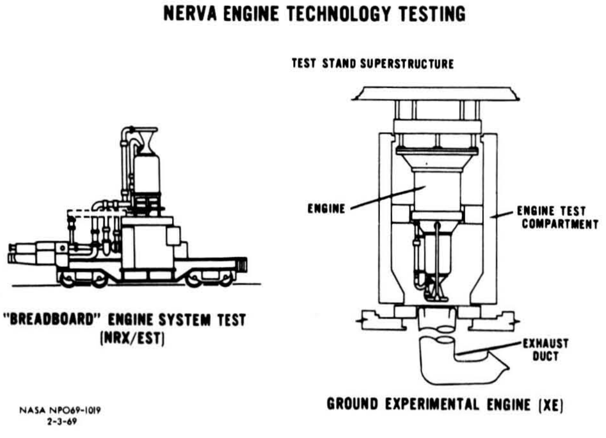


FIGURE 6

The actual configuration of XE is shown in figure 7 which is a photograph taken of the engine in the test stand, ETS-1, at NRDS. An internal view of the XE engine is shown on figure 8. It illustrates the test stand adapter and propellant shutoff valve, the upper subassembly including the turbopump, and the lower subassembly including the reactor, nozzle and various lines. Finally, to complete the configuration of test equipment, figure 9 is a recent photograph of ETS-1 showing the engine test compartment, side shields, run tank and exhaust duct.

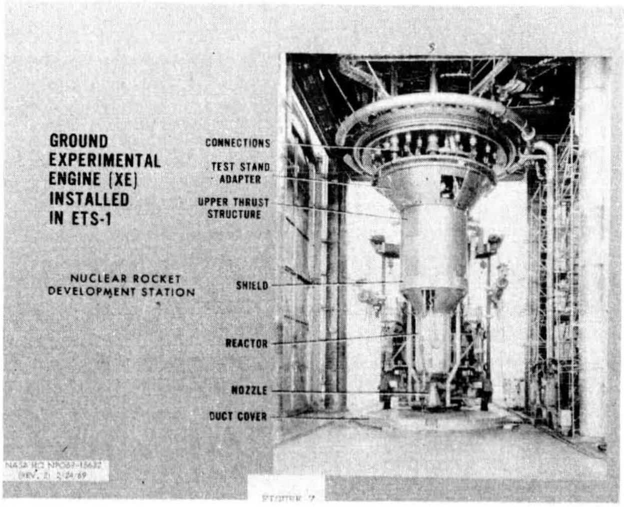
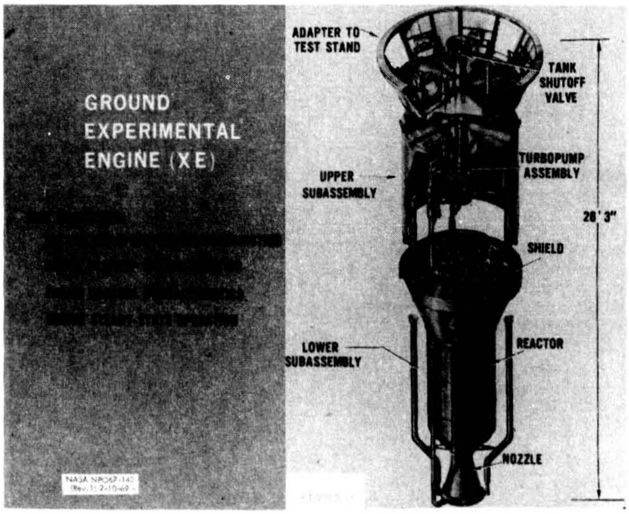


FIGURE 7



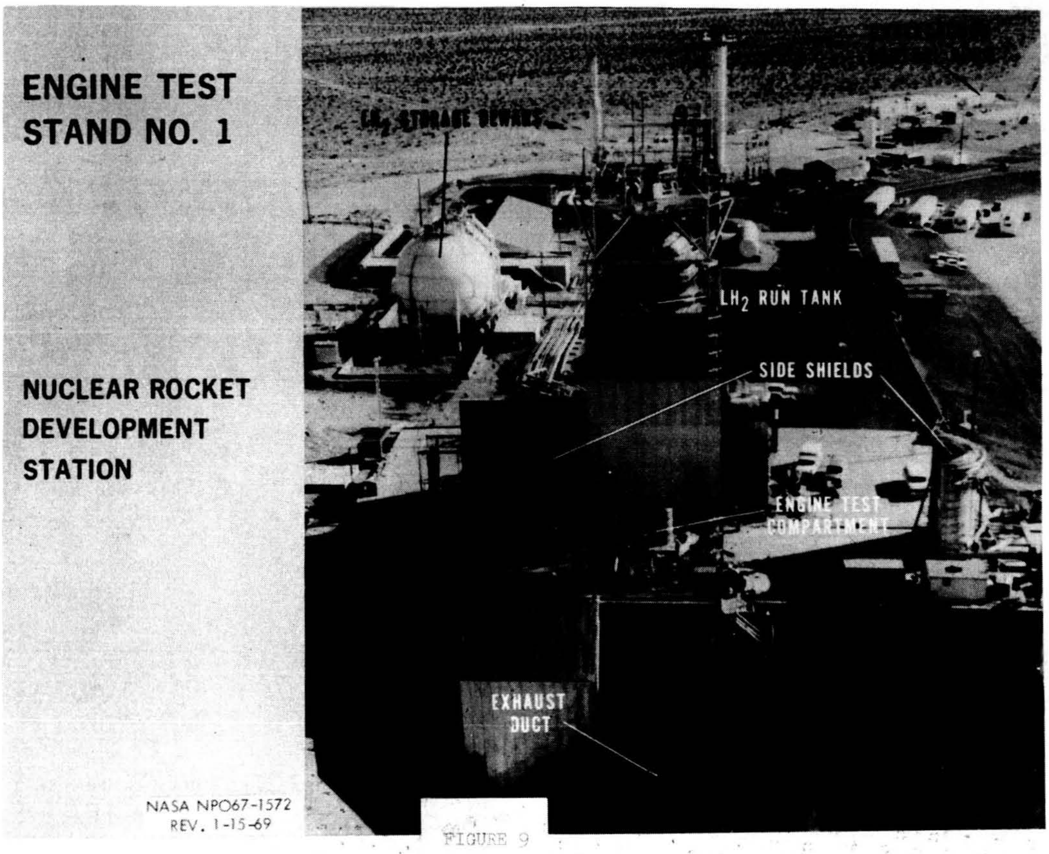


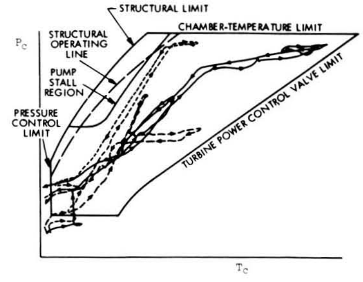
FIGURE 9

On August 28 of 1969, the XE experimental nuclear rocket engine was put through its last two test operations. These tests were high impulse start-ups to determine how the engine could be brought to power while maintaining an exit gas temperature as high as possible to minimize the impulse lost while the engine is at low power. These tests, the final in the XE engine series, made a total of 28 tests on this engine in the period beginning March 20, 1969. The total operating time was just under four hours at various power levels in a test program summarized in figure 10. During this period of time, we had only one significant component failure and that component was replaced to permit continuation of the test program.

GROUND EXPERIMENTAL ENGINE (XE) TEST SUMMARY

TEST PERIOD, 3/20/69 - 8/28/69

EXPERIMENTS CONDUCTED	
STARTUP INVESTIGATIONS	15
PERFORMANCE CHARACTERISTICS AT HIGH POWER	6
ENGINE DYNAMIC PERFORMANCE	10
FACILITY EVALUATION	4



SUMMARY - 28 TEST OPERATIONS,
3 HOURS 48 MINUTES OF OPERATION

NASA NPO70-826
(Rev. 1) 1-30-70

FIGURE 10

During the XE engine series, the operation of ETS-1, a unique test facility capable of testing nuclear rocket engines in a down-firing attitude, was also demonstrated. The two special conditions which made the operation of ETS-1 of more than normal difficulty compared to chemical rocket test stands were (1) the high radiation fields surrounding the test stand, which made it necessary to operate the entire stand remotely and restricted subsystems to those capable of operating reliably in radiation fields, and (2) the down-firing of an engine with a pure hydrogen exhaust under conditions of near vacuum startup. The XE test series was an excellent test for the ETS-1 facility. The tests exercised the facility over the full range of its capabilities. Experience was gained in remotely replacing radioactively "warm" components, and in operations involving the full range of control dynamics for the test stand as well as the engine.

In summary, from the data gathered during the XE series and the preceding tests, we have learned a great deal about how to design a reliable flight engine. We have also demonstrated that the nuclear rocket is basically a highly reliable, safe, and predictable engine.

NERVA ENGINE DEVELOPMENT

During the past year the design of the NERVA engine has proceeded on schedule. We have completed the baseline design and have nearly completed the formal design review. The design baseline and specifications for the overall engine and nuclear subsystem have been thoroughly documented in accordance with the strict systems engineering approach being employed.

The resulting overall engine design is pictured in a photograph of the engine mockup on figure 11 and the cutaway drawing on figure 12. The thrust will be 75,000 pounds and the specific impulse 825 seconds. The engine will be highly reliable and safe in operation due to the use of very conservative design and employment of a high degree of redundancy in the moving parts such as valves and turbines. The endurance goal is 10 hours and the engine will be capable of many start and stop cycles, based on the requirements of an orbit-to-orbit shuttle mission with a reusable nuclear stage.

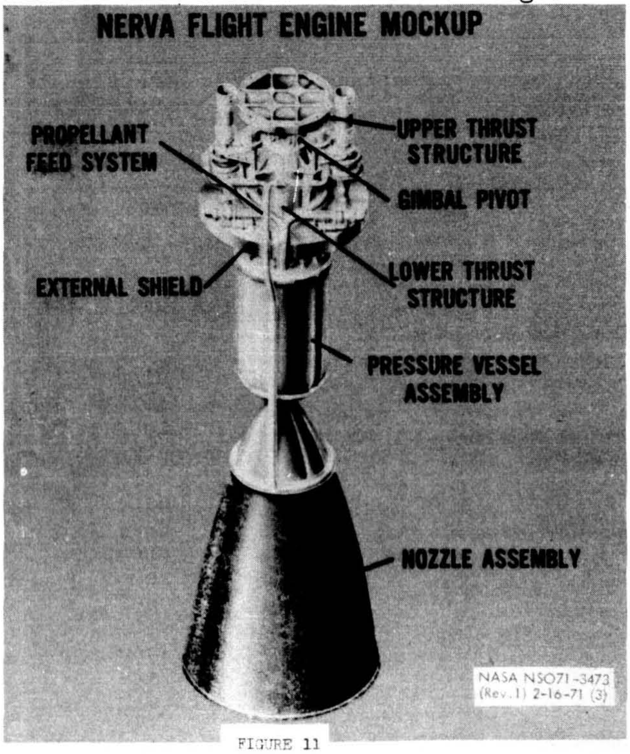


FIGURE 11

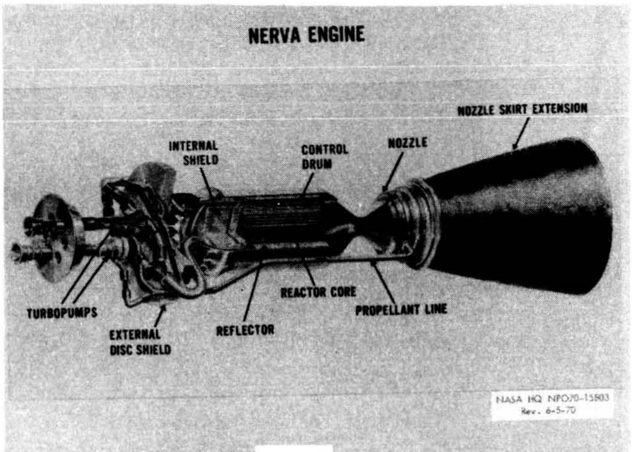
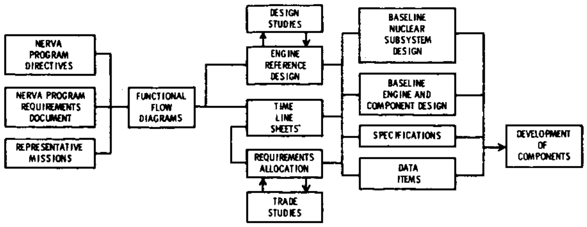


FIGURE 12

Figure 13 illustrates the systems engineering approach being used for the NERVA engine design. The design starts with the establishment of requirements and then in orderly sequence proceeds through the steps of developing functional requirements, allocating those requirements to specific components or systems, conducting design and trade studies to select designs which meet the requirements, developing designs of both the overall system and the components based on the selected concepts, and producing specifications and extensive engineering data to provide the baseline for the development of the engine. All of the activities shown on this chart with the exception of detailed component design and development are finished or scheduled to be finished this fiscal year.

With the completion of the overall design we are now in a position to intensify efforts on detailed design of the components and to release long lead-time material procurements and fabrication actions. Because of budget limitations, progress can only be made on some of the most critical of the development hardware items, including the turbopump, the nozzle extension, the reactor fuel elements and support system and the evaluation and characterization of vital materials in radiation and other applicable environments. These components will be fabricated and test programs to evaluate some of them will be started in FY 1972. In this manner, some technical progress will be made and a capability will be retained which will permit resumption of the full development program when that becomes possible.


NERVA ENGINE DEVELOPMENT

SYSTEM ENGINEERING FLOW DIAGRAM DEFINITION PHASE

NASA NSO71-3472
2-11-71

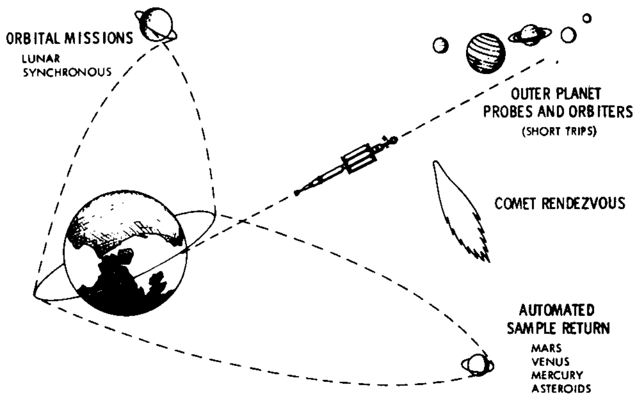
FIGURE 13

NERVA APPLICATIONS

The NERVA engine is the only practical propulsion system which can be made available to meet the requirements of many missions in prospect for the 1980's. The report of the President's Space Task Group proposed a space transportation system to cut the cost of access to space. One element of this system is a space shuttle to deliver payloads at low cost to an orbit about the Earth. The other major element is a NERVA-powered nuclear stage to go beyond the orbital range of the space shuttle. The high specific impulse of the NERVA engine, with the potential for further performance growth, makes it a flexible, economical propulsion system for a wide range of applications.

When it becomes appropriate to resume manned lunar exploration after the Apollo program is completed, a system with the capability of the NERVA engine will be needed to transport men and equipment to and from the moon (figure 14). The NERVA-propelled nuclear stage could provide transportation of automated spacecraft for exploration of the surfaces of Mars, Venus, Mercury, some of the moons of Jupiter and certain asteroids. The return of samples to the Earth will be possible in some cases. In addition, the nuclear stage could send spacecraft on fast trips to the distant planets, reducing trip times by several years in comparison to other propulsion units. Another application would likely be to move large payloads between low and synchronous orbits or from one orbital plane to another. It is expected that at least some of these missions will occur early in the 1980's. In fact, it is possible that nearly all complex missions beyond those in low orbit could be planned around the use of the NERVA stage in much the same manner that the space shuttle is considered to be the launch vehicle for virtually all purposes.

NERVA MISSIONS



NASA NSO71-3453
2-3-71

FIGURE 14

Nuclear Stage Definition Studies

In order to provide information on nuclear stages needed for mission analysis, engine design, and program planning, studies are conducted under contract to define the characteristics of a complete system for use with the NERVA engine. Illustrative of this work are the sketches (figure 15) of the various nuclear stage configurations under study. These range from the single, large-tank version to the cluster of multiple small tanks each one sized to fit within the cargo bay of the orbiter stage of the space shuttle.

The configurations on the left side of figure 15 show how shielding considerations affect stage design. The long conical aft bulkhead provides added distance between the source of radiation and a detector at the payload end of the stage and eliminates the scattering centers that would be present in a conventional ellipsoidal aft bulkhead. The modular tank concepts achieve desired distance and tank geometry through proper arrangement of the tanks. Vehicles with large single propellant tanks could be launched into Earth orbit with the Intermediate-21 or an equivalent disposable launch vehicle

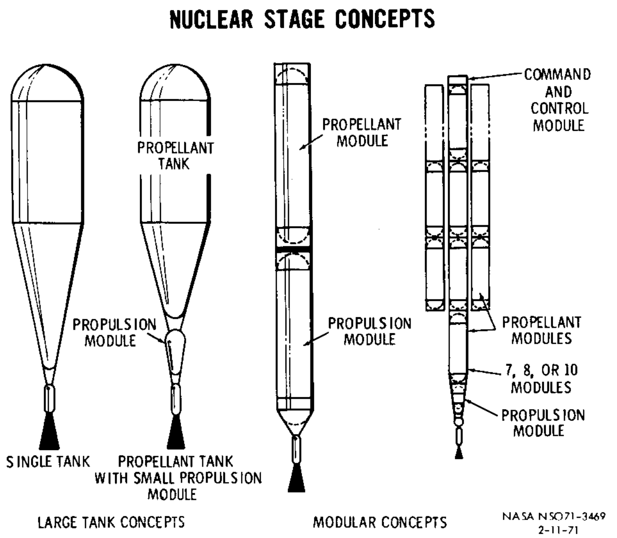


FIGURE 15

and then reloaded with propellant by space shuttle flights. Other nuclear vehicle configurations might be launched by the space shuttle (figure 16). These modular vehicles launched the the shuttle are particularly versatile since the size of the vehicle can be changed to fit many types of lunar and planetary science missions by varying the number of propellant modules.

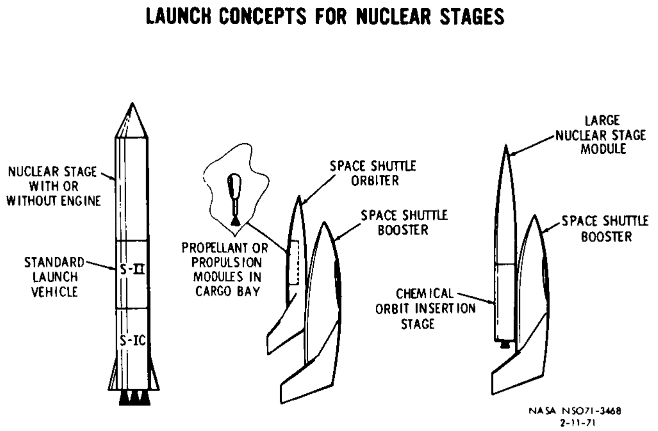


FIGURE 16

Lunar Shuttle Applications

A typical use of the nuclear vehicle in the reusable orbit-to-orbit mode would be in support of manned lunar operations in which lunar stations or bases, equipment and supplies are delivered from Earth orbit to the lunar vicinity and personnel are rotated on a regular basis. A nuclear vehicle with a usable propellant capacity of 305,000 pounds (8 propellant modules) would support a minimum manned lunar program with an average of six flights per year. A two-stage chemical vehicle capable of supporting the same lunar program would require a total usable propellant of 520,000 pounds; the corresponding Earth-orbit departure weight would be nearly 705,000 pounds.

Solar System Exploration With NERVA Engine and Stage

The nuclear stage concept formed by assembling shuttle-launched propellant tanks has some interesting prospects for conducting missions to explore the solar system with automated spacecraft. First, the system could be made available to perform prospective energetic missions in the early 1980's. Second, the nuclear stage could be tailored to suit the mission requirements of payload and energy by choosing the number of propellant tanks needed. Third, the NERVA engine could be operated at high specific impulse since short operating times would be required. Fourth, additional performance gains can be achieved by disposing of propellant tanks as they are emptied. The sum of all these features is a propulsion system that is flexible and economical with the capability to perform a range of missions, including very demanding ones.

One mission we have examined is the return of samples from the surface of Mars by means of an automated spacecraft. A nuclear stage configuration consisting of 5 propellant tanks can deliver a payload of 35,000 - 65,000 pounds into orbit around Mars. This payload would allow 160-240 pounds of material to be selected by roving vehicles from two or three different locales of the Martian surface for return to Earth. The mission duration would be about 600 days.

Studies of sample return missions from other bodies in the solar system are in process or planned. Preliminary results show that this nuclear stage could make it possible to recover samples of the Venusian atmosphere (if not the surface), of the surface of Mercury, and of many asteroids.

Another interesting application for the reusable nuclear stage would be to deliver orbiting automated laboratories to the distant planets. A preliminary study of such missions shows that the NERVA-propelled stage of only 4 propellant tanks could carry 4000 pounds of payload to an orbit about

Jupiter on a trajectory that consumes only 500 days of travel time. The short trip time of the nuclear rocket is preferred for the sake of an increase in probability of mission success and to speed the return of data to the scientific investigators.

Short trips to the planets beyond Jupiter would also be much desired. The NERVA-propelled stage could deliver about 4000 pounds of spacecraft to Neptune in approximately 6.5 years on a direct flight and in 4.8 years with an assist from a Jupiter swingby, a performance capability comparable to a 100-kilowatt electric propulsion system having a specific weight in the range of 30 kilograms per kilowatt.

In addition to this propulsion capability, it appears that the NERVA engine could also be designed, if desired, to provide 15 to 25 kilowatts of electrical power for long periods of time. A study managed by Marshall Space Flight Center has described a technique for generating this much power from the NERVA reactor with only relatively straightforward modifications in the basic engine and with little or no extension of power-conversion technology. In the power-generating mode, the NERVA reactor would be operated at low power levels (100 kilowatts) and low temperatures. A separate flow-loop through the reflector region would carry the energy from the reactor to a power conversion unit. In addition to providing power, this kind of system would reduce and simplify the after-heat removal from the NERVA reactor following operation in the high-power, rocket-engine mode.

SUPPORTING AND ADVANCED TECHNOLOGY

The nuclear rocket program continues to fund research and advanced technology activities aimed at realizing the full potential of nuclear energy for space propulsion. Some of this work extends the technology of solid-core nuclear rocket engines to high levels of specific impulse and power density. Other activities are providing a base of technology for development of a nuclear stage, and studies are conducted to define characteristics and capabilities of nuclear stages. A program of applied research and engineering studies is conducted to evaluate the feasibility of advanced nuclear propulsion concepts including both fission and fusion reactions as sources of energy.

Advanced Propulsion Concepts

While NERVA represents a major advancement in space propulsion, nuclear energy can potentially provide even greater improvements in performance of space missions beyond that possible with NERVA. In technical terms, nuclear processes yield the highest known specific energy (energy per mass of reactants) releases. Theoretically, nuclear energy could produce a specific impulse of 1 million seconds; however, there are major technical problems that prohibit the attainment of the ultimate in performance. The existence of this vast potential for nuclear propulsion stimulates programs to extend technology and to explore the feasibility of new concepts for utilizing nuclear energy to the maximum practical extent.

Structural limitations associated with solid fuel elements restrict the specific impulse of NERVA-type systems to 1000 seconds. For many years, the nuclear rocket program has conducted research and studies to ascertain the feasibility and performance potential of nuclear fission reactors in which the fuel is in the gaseous state and for which the potential specific impulse is as high as 5000 seconds. These systems are classed as gas-core nuclear rockets. Two concepts are receiving attention at this time, the coaxial flow and light-bulb reactors.

The coaxial flow reactor consists of a large nearly spherical cavity surrounded by a moderator-reflector system (figure 17). Vaporized uranium would be centered in the cavity, held there by the action of the hydrogen propellant flowing through the porous walls of the cavity. Heat generated in the fissioning uranium plasma would be transferred to the hydrogen by thermal radiation. The light-bulb reactor consists of several cylindrical cavities each containing a transparent wall of fused silica used to separate the gaseous uranium from the hydrogen propellant (figure 18). (In contrast to the coaxial concept, no uranium would be carried away with the hydrogen stream.) Thermal radiation must pass through the transparent wall in order to heat the hydrogen to desirable temperatures.

COAXIAL-FLOW GAS-CORE NUCLEAR ROCKET

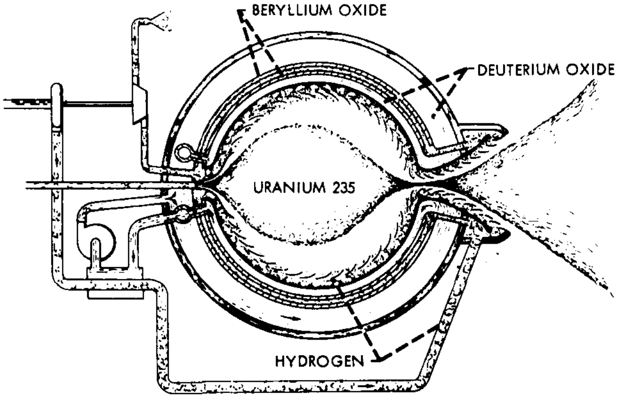


FIGURE 17

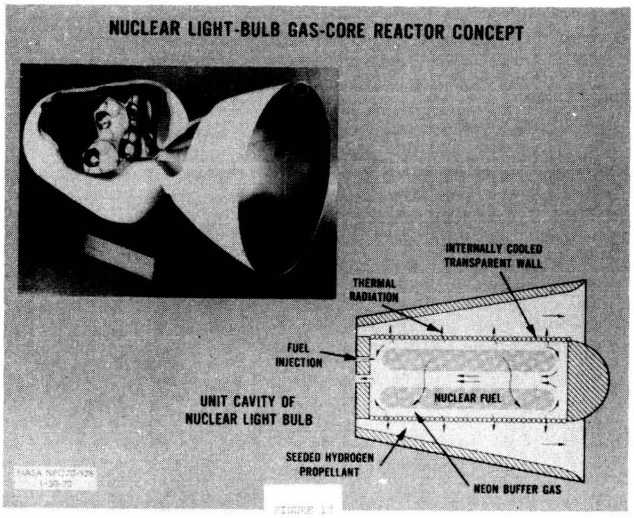


FIGURE 12

In both concepts, we are dealing with very difficult questions of feasibility, and there are a number of NASA-sponsored research programs involved in getting answers. While this work is broad in scope it is limited to studies of fundamental problems. Basic studies are conducted to define the emission and absorption of thermal radiation in uranium and hydrogen plasmas at high temperatures and pressures. The use of ultra-fine particles to "seed" hydrogen to make it opaque is the subject of experimental programs and considerable effort is devoted to providing electrically-heated plasmas hot enough to explore thermal problems of gas-core reactors. Other research includes fluid mechanics, radiation-effects on transparent materials, system analysis, and stability of high-density plasmas.

Progress in these gas-core programs has been encouraging within the context of the limited funding applied in this area. Some of this progress is as follows. Plasmas have been produced with equivalent radiating temperatures hotter than the Sun. In a small but significant first step, seeded hydrogen has been heated for the first time in a laboratory by thermal radiation alone to temperatures in excess of 4000°R. Small scale tests of a coaxial flow reactor configuration have been conducted with induction-heated plasmas, and a porous wall, and vaporization of a solid to simulate formation of a uranium plasma. In the area of systems studies, analyses have shown a coaxial-flow gas core reactor may be capable of achieving a specific impulse in the range of 5000 seconds.

Other concepts besides these gas core reactors are being studied in the nuclear rocket program. This past year we initiated a small program to investigate a dust-bed reactor concept and its potential for a high-power density. A unit such as this would be useful in applications where high-thrust and moderate engine weight are essential. In addition, we began sponsorship of some research at the Lewis Research Center into that area of plasma physics related to the production of propulsive thrust from a controlled fusion reaction. This step appeared appropriate in view of the progress reported recently in the fusion research programs throughout the world.

Recently reported advancements in pulsed-lasers and predictions that fusion plasmas could be produced thereby have generated interest in this form of energy production. LASL has begun studies and research into the means by which a laser-ignited fusion reaction could be applied to propulsion and power generation. Indications are that high specific impulses could be produced at high thrust levels.

It is not possible to say at this time, as we can for the NERVA engine, whether any of the advanced systems described above can be successfully developed. The technology is extremely difficult. In spite of these difficulties, we are of the opinion that research into the feasibility of all these advanced concepts should continue at a modest level of funding. Through support of this research, breakthroughs may be stimulated or we may find the job in some areas to be less difficult than now expected. Even if this does not happen, the very nature of these advanced propulsion concepts places the research at the frontiers of technology in high temperature plasmas, radiant heat transfer, lasers, fluid mechanics, materials, etc. The output of this research will be beneficial in many areas even if a new propulsion capability is not produced.

REFERENCE

1. Corliss, W.R. and Schwenk, F.C.: Nuclear Propulsion for Space. United States Atomic Energy Commission Division of Technical Information. Library of Congress Catalog Card Number 67-61704, 1971.